Seeing the soil through the trees: The utility of stem shape and taper in the butt swell for predicting soil depth in Australian *Pinus* plantations.

by

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Candidate's Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university. To the best of the author's knowledge, it contains no material previously published or written by another person, except where due reference is made in the text.

Jie-Lian Beh

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Abstract

An increasing proportion of the world's wood is grown in plantation forests, so improving management of these forests is important for global wood supply, as well as for the profitability and sustainability of individual plantation estates. Plantation forests have historically been managed on a relatively coarse scale, with plantation sites classified into site quality classes that are typically tens of hectares, or more, in extent. While this approach allows forest managers to apply the most appropriate silvicultural and management practices to suit the soil and environmental conditions of that particular site quality class, it necessarily overlooks the finer-scale variation that is typical of almost all plantation sites. "Precision forestry" is an emerging approach that, like precision agriculture, matches management to fine-scale variation in site conditions.

Managing plantations at this scale requires a much more detailed understanding of spatial variation in soil resources than has been the case in the past. However, current approaches to soil mapping are constrained by the logistic limitations and considerable expense of soil sampling. For this reason, finer-scale soil mapping across the large areas that characterise plantation estates is not feasible. Relationships between soil properties and attributes of tree growth are well established for major plantation species. The relationship between soil properties and stem shape and taper in the base or butt swell section of the tree stem has not previously been established or quantified, but physiological models of stem development suggest an association between this section of the stem and the quantity of soil resources. Although the relationship between site and tree height (site index) is already well established, obtaining accurate measurements of tree height using conventional field methods is often difficult in closed stands.

This thesis investigated the nature and utility of the stem shape and taper-soil relationship; and compared this to the well established tree height-soil relationship. Sampling to address this topic was conducted at a series of case study plantation sites in southern and eastern Australia. The first stage of the research sought to establish whether there was any relationship between soil depth class and stem shape in the bottom 2 m of the tree stem. A proof of concept study was conducted at contrasting *Pinus radiata* plantation sites in the Australian Capital Territory (ACT) and Tasmania; before work was extended to a third contrasting *P. radiata* site in south-eastern South Australia, and then to two further *P. radiata* sites on the southwest slopes of New South Wales (NSW). These sites were selected to sample much of the diversity of *P. radiata* plantation sites in south-eastern Australia.

A regression model for predicting soil depth from tree shape measurements in the basal 2 m of the stem was developed and improved progressively as data was acquired from each case study site. Statistically significant parameters in the model were stem shape, taper and a term to account for differences between regions. Stem shape and taper in the butt-swell section of the stem was found to be strongly and predictably related to soil depth across all sample sites, which encompassed a broad range of soil types and depths. Soil depth was represented initially, in terms of depth class, and subsequently, as absolute soil depth to a root-impeding layer.

The ability of the shape-taper model to predict other soil properties including nitrogen, phosphorus, total organic carbon, and water holding capacity were also explored. It was possible to predict simple linear relationships, such as that between available nitrogen and taper, but more powerful relationships could not be successfully fitted. This was likely due to the limited sample size and interactions between variables.

The stem shape-taper model was applied to mapping fine-scale soil depth variation in south-east Queensland. At its current stage of development, the model requires calibration for the location at which it is applied from a relatively small number of soil depth measurements. The quality of the map generated by the model was found to be equivalent to that produced using the conventional method of soil mapping; and better than the map generated by a model based on tree height. In addition to these findings, the mapped spatial variation of stem shape and taper in the butt swell section was found to reflect relative changes in soil depth. This represents a potentially useful alternative approach in cases where only relative depth variation is required that would be even cheaper and simpler to implement.

The results of the research reported in this thesis are encouraging for fine-scale soil mapping in plantation forests. They suggest, firstly, that variation in the shape and taper of the butt swell section of the tree stem can be used to predict soil properties – certainly soil depth, and possibly, with further development, other soil properties relevant to tree growth; and secondly, that there is considerable promise for a simple tree-based approach to mapping fine-scale spatial variation in at least soil depth, and perhaps other soil properties. This, in turn, offers the prospect of a feasible and low-cost means of generating the information necessary to support finer-scale plantation management, such as that envisaged by precision forestry.

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List of acronyms and abbreviations

ACT	Australian Capital Territory	
NSW	New South Wales	
SA	South Australia	
TAS	Tasmania	
QLD	Queensland	
DBH	Stem diameter at breast height over bark (1.3 m in Australia)	
d	Stem diameter over bark at height h	(m)
H	Total tree height	(m)
h	Height above ground on uphill side at diameter d	(m)
b	Stem shape relative to DBH	(unit-less)
k	Stem taper relative to DBH	(cm/m)
β	Model coefficient	
m	Metres	

Chapter 1: Introduction

1.1 Background

Commercial plantation estates have been established on large scales in a number of regions of Australia. These are typically hundreds or thousands of hectares in extent and encompass a diverse range of climate, terrain and soil conditions. Hence, the stratification or classification of plantation land into smaller management units or site quality classes on the basis of environmental factors enables the application of the most appropriate silvicultural and management procedures to each site class to optimise production across the plantation estate. Site classification has been the fundamental approach to all plantation management in Australia since plantation forestry began in the country more than a century ago. The level of sophistication of this classification has varied over time, and between plantation growers; in Australia, the South Australian site classification system exemplifies the operational-scale incorporation of such stratification into plantation management.

Over the last decade, this has been taken further with the advent of precision forestry, an emerging concept globally which has originated from the same principles as those of precision agriculture. Both precision agriculture and precision forestry seek to optimise production by matching management to site conditions at a fine scale using geospatial technologies and information systems, with both potential productivity and environmental benefits. One of the main goals of precision forestry is to reduce the size of management units from the traditional plantation compartment or stand-level, typically tens of hectares in extent, to almost the level of the individual tree. As the soil is the most important factor of environment influencing the growth of the individual tree, the precise management of plantation trees therefore relies on understanding the fine-scale spatial variation of the soil resource.

The utility of detailed soils information as a basis for improving the performance of silvicultural activities and forest operations is widely acknowledged by forest growers. However, forest soil surveys have had limited scope in Australia, and maps of forest soil properties, where they do exist, are more generally available at broader (e.g. 1:100 000), rather than at finer (e.g. 1:25 000) scales. Although existing approaches for mapping soil properties are well developed, these approaches are typically constrained by the expense and logistic limitations of soil data collection. In contrast to agricultural lands, forested areas have high degrees of spatial heterogeneity in site and soil conditions which further complicates the task of soil sampling and measurement. Sampling at sufficient intensities to produce detailed maps of soil is often time consuming and costly. Developing detailed maps of soil properties across the whole plantation estate requires alternative approaches to soil sampling and measurement that are inexpensive, efficient and easily implemented.

As trees express and integrate site and soil conditions in their growth, individual tree measurements may be considered the integrated expressions of the quality and quantity of the soil resource. The relationship between tree growth and soil properties has been the basis for many methods of site quality classification, especially for more detailed delineation of site classes. As a result of considerable research over the last century of plantation forestry, many relationships between measures of tree growth, such as tree height, and soil properties have been established. These relationships have typically been applied at the stand-level in site quality assessment to predict tree performance from soil properties; however, implicit in this approach is the potential to conversely, predict soil properties from tree characteristics. The ability to obtain point estimates of important soil attributes, such as soil depth, from simple measurements of individual trees, rather than from direct soil sampling, would reduce or potentially eliminate many of the current logistic constraints to mapping fine-scale spatial variation in soil properties.

Soil properties have been most frequently related to stand-level measures of tree height, such as site index, in soil-site research. However, ground-based methods of measuring individual tree height are difficult and even impossible to implement under closed canopy conditions. For this reason, the measurement of tree height is often one of the most time-consuming components of a forest inventory program. The shape and taper of the butt swell section or base of the tree stem are more easily measured from the ground. Changes in stem shape and taper in this section of the stem have been associated with differences soil properties, but the relationship has not previously been quantified. Stem shape and taper of trees have traditionally been of interest to forest growers for the estimation of wood volume and determination of yield tables. However, shape and taper in the butt swell section of the stem is often ignored in stem shape determinations for two main reasons: 1) it is highly variable and therefore, difficult to predict accurately; and 2) it does not contribute to the merchantable volume of the stem; hence, from a forest management perspective, understanding the development of shape in the butt swell section has not been a high priority for research.

From a physiological or functional perspective, the increased growth allocation that comprises the butt swell section has been attributed to the development of the root system and anchoring of the tree. Research on the physiological development of stem shape further suggests that the extent of growth in the butt swell is related to soil resources, in particular with the depth of the soil. As soil depth is one of the most important soil characteristics influencing tree growth, a more efficient method of mapping spatial variation in soil depth properties would make a significant contribution to improving the performance of many soil-related silvicultural activities and forest operations. To investigate this topic, this thesis draws on research from several areas of study, including: forest soil survey and mapping, site evaluation and soil-site studies, and the theories of stem shape development. These topics are reviewed in Chapter 2.

1.2 Thesis aims and objectives

This thesis is based on the premise that there is a quantifiable relationship between soil properties and stem shape and taper. As there is no precedent in the academic literature for such an approach to soil prediction and mapping, the literature review in Chapter 2 of this thesis draws on the numerous soil-site studies that investigate the relationship between soil parameters and tree growth. These relationships have historically been of interest to forest managers for the purposes of improving site evaluation. This thesis however, uses the well established tree-soil relationship as a basis for improving and reducing the cost of predicting and mapping variation in forest soil properties. Specifically, this research investigates the relationship between stem shape and taper in the butt swell section of the stem and soil depth properties and explores the practical utility of using the relationship to predict and map fine-scale spatial variation in soil depth.

The study was divided into a series of stages (Figure 1.1). Early stages of work sought to establish a relationship between stem shape and taper in the butt swell and soil depth for model development. Subsequent stages of work aimed to improve and extend the model by the incorporation of more data from a range of study sites and different tree species. The possibility of using stem shape and taper to predict a range of other, more detailed soil properties was also explored. The practical application of the model to mapping spatial variation in soil depth within a plantation compartment was demonstrated in the final stage of work.

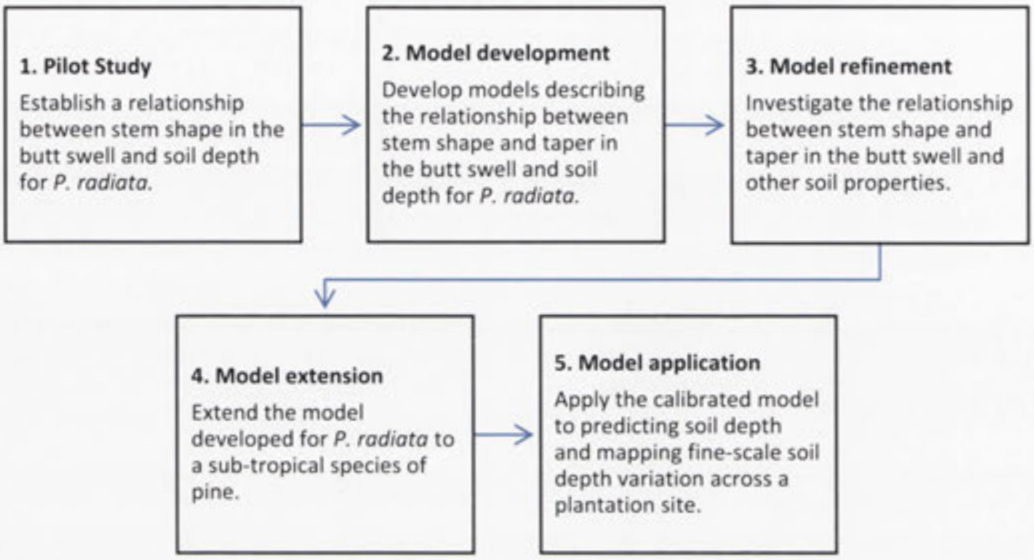


Figure 1.1 Study approach and main objective for each stage of work.

1.3 Thesis outline

The thesis is structured as follows:

Chapter 1, the Introduction – places the research in context, provides an overview of the thesis and lists the major aims and objectives of the research.

Chapter 2, the Literature Review – reviews the literature on precision forestry, existing methods of soil mapping and the study and traditional application of the relationship between tree growth and soil properties in forestry for site classification. The literature on the development of the shape and taper of the stem profile with particular focus on the butt swell section of the stem is also summarised.

Chapter 3, Study approach, site descriptions and general methods – provides an overview of the study approach, general descriptions of case study regions, and methods used for field sampling, data analysis and model development and testing.

Chapter 4, Establishing the relationship between stem shape and taper in the butt swell and soil depth – presents results from work conducted in the Australian Capital Territory and Tasmania. This chapter describes the first stage of work in which a preliminary model for predicting soil depth class from measurements of tree shape and taper in the butt swell section is proposed. Small samples of trees from ACT and Tasmanian plantations were measured in soils classed as either relatively shallow or deep. Data was analysed to investigate whether stem shape and taper in the butt swell were statistically significant predictors of soil depth.

Chapter 5, Developing the soil depth model in South Australia – presents results from the South Australian case study site. This chapter focuses on the development and optimisation of the preliminary model for predicting soil depth class developed in the previous chapter, by using a more extensive set of data from a third plantation growing region in Mount Gambier, South Australia. In this stage of work, soil depth was both classified and measured. The dataset from South Australia was used to develop a second, preliminary model for predicting absolute soil depth from shape and taper in the butt swell section of the stem.

Chapter 6, Improving the soil depth model and investigating the relationship with other soil properties – presents results from New South Wales case study sites. This chapter investigates the potential for using stem shape and taper in the butt swell to predict more complex soil properties important to tree growth, such as nutrients, carbon and water storage capacity. This chapter also describes the further improvement of the developed models for predicting soil depth class and absolute soil depth by addition of the data collected from this stage of work.

Chapter 7, Extending the model to subtropical pine and improving spatial mapping of soil depth – develops the model for a subtropical species of pine and demonstrates the practical application of the calibrated model for mapping soil spatial variation at a plantation site in Queensland.

Chapter 8, Synthesis of results and concluding discussion - reviews the major aims and hypotheses of the thesis and discusses them in relation to the overall results.

Chapter 2: Literature Review

2.1 Outline of the chapter

This chapter reviews the literature relevant to the thesis and provides a basis for the research approach. The chapter briefly outlines plantation forestry in Australia, before describing the renewed need for soils information at finer scales with the emergence of precision forestry. The chapter then reviews past and current approaches to soil measurement and modelling; the relationship between soil properties and tree growth, and how this relationship has traditionally been applied in forest management. Physiological theories of stem shape and taper development are briefly reviewed; before concluding with a précis of the state of knowledge relevant to the objectives of this thesis.

2.2 Australia's plantation forest estate

Plantation forestry first began in Australia more than a century ago and now dominates the Australian forestry and timber industries. Plantation forests were established on large scales throughout the 20th century. Plantings were initially of softwoods and more recently, of hardwoods (Gerrand, Keenan et al. 2003). The total area of Australia's plantation forest estate now exceeds 2 million hectares. Plantations comprise less than 1 % of the country's total forest estate, but supply two thirds of Australia's industrial wood production. Significant increases in this supply, particularly of hardwood pulp, are projected over the next 20 years with the continued expansion of the plantation estate and long-term decline in the volume of timber being harvested from native forests (BRS 2010).

Plantation areas in Australia are largely located in higher rainfall regions along the coast; from the wet tropics of north Queensland and the Northern Territory, to the southern-most regions of Western Australia and Tasmania. The entire estate comprises about 1.02 million ha of softwood, mainly *Pinus sp* but with about 50 000 ha of the native *Araucaria* *cunninghamii*, grown principally for sawnwood, 0.99 million ha of hardwood, mainly Eucalyptus dominated by *Eucalyptus globulus* and *Eucalyptus nitens*, almost all grown for pulpwood and a small area of mixed plantings. Production from plantation forests is a significant industry in six states: New South Wales, Victoria, Queensland, Western Australia, South Australia and the Australian Capital Territory. New South Wales and Victoria are the largest producers, reflecting the scale of their established softwood plantations (McDermott, Cashore and Kanowski 2010). Nationally, the longer rotation softwood plantation estate is mature but the rate of expansion has slowed in recent years, while the shorter rotation hardwood plantation estate is relatively immature but has been rapidly expanding at an average rate of 70 000 ha annually over the past decade. Eucalypt plantations have been expanding in most Australian states, mostly in South Australia, Tasmania, Victoria and Western Australia (ABARE 2011).

Industrial wood is the dominant product in terms of volume and value harvested from Australia's forests. Total wood harvest is approximately 27 million m^3, the majority of which is from plantations, with about 14 million m^3 from softwoods and 4 million m^3 from hardwoods. The gross value of this production is $1.7 billion. Plantations provide a range of non-wood forest products, the largest of these, is apiary products worth $ 49 million. In total, the forestry sector accounts for 1 % of Australia's gross domestic product (McDermott, Cashore and Kanowski 2010). Australia's reliance on plantations for wood supply is increasing, and there is now a further expectation that planted forests can be used to provide other environmental services and values such as carbon sequestration, water quality and quantity improvement, salinity mitigation and habitat for native plants and animals (Gerrand, Keenan et al. 2003).

2.3 The shift toward precision forestry

Commercial plantation forests are playing an increasingly important role in supplying the world's demands for wood (Kanowski and Murray 2008). Therefore, improving management of these forests is critical to improve and sustain productivity, while delivering or protecting ecosystem values and services. "Precision forestry" is an emerging concept that is currently shaping the management of commercial forests worldwide (Taylor, McDonald et al. 2006). The concept of precision forestry originates from the same philosophies as those of precision agriculture, a now widely accepted concept in global agriculture. Precision agriculture aims to improve crop performance, while reducing waste, increasing profit and maintaining environmental quality (McBratney, Whelan et al. 2005). The concept of precision agriculture in cropping systems emerged in the late 1980's with the matching of grid-based sampling of soil chemical properties with the then newly developed variable-rate equipment for the application of fertilisers (Whelan and Taylor 2010). Since that period in time, new systems for measuring or inferring soil and crop parameters on a more continuous basis have been developed, using both on-ground and remote sensing platforms. The success and rapid adoption of precision agriculture principles and technologies for crop production over the last 20 years, together with growing concern about the long-term ecological sustainability of forest management practices, has prompted the forest products industry to move toward a similar management approach.

As the forest products industry differs from the agricultural sector in many ways, not all the concepts of precision agriculture are applicable to forest production systems. Because of these differences, the term 'precision forestry' has been differently and more broadly defined (Taylor, McDonald et al. 2006). The term also has different meanings depending on the context in which it is used. It has most frequent use in the context of more efficient production of high quality timber and fibre products, but it is also applied to the more precise management of the forest to optimise environmental benefits. There are many different applications in forest management that can be considered a part of precision forestry. These range from the use of advanced technologies to measure wood quality and quantity traits, to developing site-specific management systems that match species to site and enable delivery of precise silvicultural or ameliorative treatments to improve wood quality, augment nutrition and control competing vegetation (Jokela, Martin and Vogel 2010).

Taylor, Veal et al. (2006) define precision forestry as planning and conducting site-specific forest management activities and operations to improve wood quality and utilisation, reduce waste, increase profits, and maintain the quality of the environment; and propose that the subject be divided into two main areas of focus: 1) using geospatial technologies to support site-specific forest management and planning; and 2) conducting site-specific silvicultural operations. The first area of focus encompasses those management and planning activities that have an emphasis on site-specific management and includes both more traditional practices, such as the use of geospatial information systems (GIS) to develop forest management plans, and newer approaches, such as the use of information technology to optimise transportation of wood products from forest to processing location. The second focus likewise involves the use of geospatial technologies, but with the goal of improving operational efficiency and reducing the cost of wood fibre. This employs much of the technology developed for agricultural systems, such as variable rate controllers to improve the efficiency of herbicide or fertiliser application (Taylor, Veal et al. 2006).

The key characteristics common to all forms of precision forestry are 1) the use of geospatial technologies such as, GIS, global positioning systems (GPS) and remote sensing, as tools to assist in site-specific forest management, planning or silvicultural operations; 2) the development and use of a comprehensive information database, which may include data on product growth and yield, product quality, and environmental conditions, as bases for making decisions; and 3) the ability to define the most appropriate management unit, which involves examination of stand maps, and terrain, soil and site maps (Taylor, Veal et al. 2006).

The work presented in this thesis is most relevant to this last characteristic of precision forestry. Defining the most appropriate management unit requires the development of new methods or optimisation of existing methods that characterise fine-scale spatial and temporal variability in climate, site quality and growth conditions. One of the primary goals of precision forestry is the gathering of site specific information, which has the potential to reduce management units from the traditional stand level to almost the level of the individual tree. New and existing technologies are being applied to all aspects of the forest management and wood supply chain to characterise site variability at a finer scale and enable more precise management and planning (Farnum 2001). One of the more promising technological advancements is the use of laser mapping methods, such as light detection and ranging (lidar), which offers the potential to collect detailed information on individual tree attributes more efficiently and over large areas (Anderson, Reutebuch and Schreuder 2010; Danilin, Medvedev and Sweda 2010).

At the scale of the individual tree, the most important factor of environment influencing local variation in growth is soil properties. Unlike agricultural systems, where soil type is relatively uniform within a field, soil properties are known to vary widely over short distances in forested sites, in response to more variable topography and the absence of tillage to mix and homogenise soil surface layers (Courtin, Feller and Klinka 1983). Planning and implementing site-specific silvicultural activities and operations is a key component of precision forestry that requires a detailed understanding of forest soil variability. For example, patterns of soil depth variation across a site indicates the amount of water storage available which enables forest managers to implement forest operations, such as tree selection for thinning, to maximise tree survival particularly during drought-affected summers.

Further to this, important silvicultural activities, such as site preparation, fertiliser and weedicide application, thinning and harvesting influence both wood production and the plantation environment through their impact on the soil. Many silvicultural activities are ground-based operations that involve the use of heavy machinery, which also require road systems for their operation (Worrell and Hampson 1997). One of the most detrimental impacts of mechanised silvicultural activities to site productivity is soil compaction (Sands, Greacen and Gerard 1979; McMahon, Simcock et al. 1999; Simcock, Parfitt et al. 2006). A detailed understanding of variability in soil properties is therefore fundamental to both improving implementation of site-specific silviculture, and minimising the impact of forest operations on long-term site productivity. A method for predicting soil depth properties from tree shape attributes would be relevant to both those forest operations and silvicultural activities performed in the compartment in the same rotation as measurement and in subsequent rotations if tree measurements are performed at or near final harvest.

2.4 Description, management and mapping of forest soils

2.4.1 Forest soils

Soil supports the growth of forests, but is also a critical natural resource in itself. The soil may be defined as a complex mixture of mineral materials, organic matter, water, air and living organisms. The soil mantles most of the earth's terrestrial surface and varies in depth from a few centimetres to several metres. The physical texture and structure of soil controls the infiltration, percolation, and storage of water; while the amount and nature of clay and organic matter, together with the influence of parent material and vegetation, determine its chemistry and fertility. The soil is an integral component of the forest ecosystem that serves multiple functions. Forest soils harbour a diversity of plant and animal life which are essential for organic matter decomposition, nutrient cycling, energy conversion and soil formation processes (Corbett 1969). The soil acts as a medium for tree growth, anchoring the tree physically and supplying water and nutrients for uptake by tree roots. It is a conduit for water movement and filtration, controlling the quality of water in watersheds; and is a major ecosystem component, regulating energy flow, nutrient cycling, the rate of organic matter decomposition, carbon sequestration and biodiversity (Burger 2004). Hence, improving the productivity of plantation forests, while maintaining ecological values and services, requires not only management of the trees for wood production, but management of the soil resource, on which all tree growth depends.

2.4.2 The application of forest soils information to forest management

Since the soil is so closely related to tree growth, plantation forest management has always involved the management and manipulation of the soil resource. Detailed knowledge of how the soil properties most important to tree growth vary within a forest plantation compartment is essential to improving all soil-related silvicultural and forest operations. Characteristics of the soil affect the performance of numerous soil-related activities, such as response to fertilisation, efficacy of weed control, and assessments of soil erodibility, soil moisture storage, drought potential, waterlogging, potential for windthrow, and soil trafficability (Turvey and Poutsma 1980).

Most soil properties important to decisions regarding soil-related silvicultural and forest operations are related to soil depth, texture and structure, and drainage. Differences in soil structure and texture govern the extent of weedicide and fertiliser leaching and thus, determine the efficacy of weed control and fertilisation; while variation in effective soil depth properties, in combination with differences in soil structure and texture, influence the susceptibility of trees to the effects of drought, water-logging and windthrow. In situations where vertical root exploration is limited by shallow soils, the development of a perched water table during wet winters can lead to reduced soil strength. This increases susceptibility to windthrow. On the other hand, water supplies in shallow surface soils are more rapidly exhausted during dry summers, leading to increased risk of drought stress or death.

Detailed soils information can enhance management of the forest in a number of ways. Maps of soil textural properties for example, enable the ranking of growth response to fertiliser or estimation of weedicide efficacy. Detailed maps of soil depth variation enable the optimisation of planting or thinning operations such that tree stress or death due to drought, water-logging or windthrow may be minimised. In addition, soil depth, textural and drainage properties determine the bearing strength of the soil to support off-road vehicular traffic or soil trafficability (Turvey 1980). Thus, understanding how these properties vary allows the delineation of optimal areas for placement of roads to minimise the impacts of vehicular traffic during harvesting or thinning operations or for assessing sites for road-making capability. Managing all of these factors well has significant benefits for optimising production, minimising cost and maintaining the ecological sustainability of the soil resource.

2.4.3 Forest soil mapping in Australia

It is evident that improving soil-based forest operations and minimising their environmental impact - in other words, meeting the goals of precision forestry - relies on knowledge of soil spatial variation, both across the plantation estate and at a finer scale, within units of management (usually called "compartments" in the Australian context). However, forest soil surveys are still relatively uncommon in Australia (Thwaites and Slater 2000). Soil maps for the Australian plantation estate are more frequently available at broader scales (1: 100 000 or greater), rather than at finer scales (1: 25 000 or less). Detailed soil surveys have been conducted for some plantation sites, such as those in South Australia, but this represents a minority of cases. Intensification of production in Australian plantations has brought with it the need for detailed soils information that is available over a broader range of plantation areas. This section outlines firstly, the approaches to soil survey and mapping; and secondly, the state of detailed forest soil survey in Australian plantations.

2.4.3.1 Approaches to forest soil survey and mapping

The soil varies continuously at different scales and complexities across the landscape. Unlike the vegetative and atmospheric components of the forest ecosystem, the soil cannot be directly observed or measured as a whole (Ryan, McKenzie et al. 2000). Therefore, any knowledge of soil spatial variation is fragmentary as it is derived from the sampling of small volumes at a finite number of places. Consequently, any representation of the soil landscape must involve simplification and inference or prediction to classify or quantify soil properties between sample points. Two principle approaches to representing spatial variation in soil properties may be distinguished. The first and earlier approach, partitions soil into discrete classes and is essentially qualitative; while the other, seeks to describe and quantify the continuous variation of soil properties over the landscape (Heuvelink and Webster 2001).

In the conventional soil survey, soils are classified and mapped using the inferred relationships between soil properties and readily observed landscape features, such as geology or landform, to extend soil observations made at a limited number of point locations to the broader map unit (Ryan, McKenzie et al. 2000) (Figure 2.1). The outcome is a cartographic model, known as the choropleth or polygon map model, in which the spatial distribution of map units (e.g. soil type) are represented by discrete polygons, linked by a map legend to the attributes of a soil profile. There are several key problems associated with using conventional soil survey methods which limit their use, particularly for mapping soil variation over large areas at finer scales (Scull, Franklin et al. 2003). These are related to the sampling and measurement of soil properties; the classification of soil into soil types, and the derivation of soil attribute maps, which assumes covariance between soil type and individual soil attributes.

Obtaining information on soil properties is complicated by both the nature of soil variation, and the associated logistic limitations and expense of soil sampling and measurement. Creating detailed maps of soil using methods based on samples would require sampling at sufficiently high intensities; which is generally considered prohibitive in terms of cost and labour especially across any extensive forest area. Sampling intensity in a typical soil survey is typically stated as 1 – 4 samples per cm^2 of map (Ringrose-Voase 2011). Thus, approximately 16 samples per km^2 would be required to generate a map with a cartographic scale of 1: 25 000. By the same rule, the number of observations would increase to about 100 samples per km^2 for a map with a finer scale of 1: 10 000. The type of soil assessment conducted also contributes to the overall cost of the exercise. Rapid assessment of soil morphology would be relatively inexpensive, but detailed quantification of soil properties, especially those requiring chemical analyses substantially increases the cost of mapping.

Another key limitation of conventional soil survey relates to the classification of soil into soil types, which results in the final polygon map. Two main problems follow from this approach: 1) the lines drawn on soil survey maps may not accurately depict actual boundaries between polygons, particularly where soil changes are gradual rather than abrupt; and 2) the implied homogeneities within polygons do not exist for many physical and chemical soil attributes because many of these soil properties vary continuously across the landscape (Burrough, Gaans and Hootsmans 1997). It is also widely assumed that individual soil attributes, such as pH, vary in concert with the mapping unit, such as soil type (Webster and Butler 1976). However, the assumption of covariance between the soil attribute and map unit is rarely tested, despite having a potentially significant impact on the reliability of predictions (Butler 1980; McKenzie and Austin 1993). Due to the process of soil classification, soil maps produced by conventional soil survey often convey little of what is known about the actual variation of individual soil properties and nothing of the quantitative nature of their variation.

Technological advancement in computing and information processing over the last 30 years has facilitated the development of digital soil mapping or quantitative soil survey (Gessler, Moore et al. 1995; McBratney, Mendonca Santos and Minasny 2003). Digital soil mapping uses geographical information systems to model spatial soil variation from more easily mapped environmental variables derived from remote sensing, such as digital elevation models (DEMs). The approach has three main aims: 1) to exploit the relationship between environmental variables and soil properties to enable more efficient collection of soil data; 2) to better represent the continuous spatial variation of the soil landscape; and 3) to explicitly incorporate expert knowledge in model development (Scull, Franklin et al. 2003). In contrast to conventional soil survey methods, which begin with the soil surveyor's conceptual model of soil patterns, digital soil mapping begins with the development of numerical or statistical models of the relationship between environmental variables and soil properties (Figure 2.1). This enables predictions of individual soil properties to be generated with a stated accuracy and precision (McBratney, De Gruijter and Brus 1992; Ryan, McKenzie et al. 2000). Numerous statistical methods for the spatial extension or interpolation of soil point data have now been developed. Kriging is one such method of spatial interpolation that has been widely adopted in soil research to predict soil characteristics across a survey area (Burgess and Webster 1980). However, interpolation methods are generally limited to areas that have been intensively sampled to be effective and for this reason, can be costly to implement (McKenzie and Austin 1993).

2.4.3.2 Mapping of forest soil properties at the compartment-level

Although the utility of soils information for detailed forest site assessment has long been recognised, the use of soil survey information for improving soil-related forest activities and operations has historically had limited scope in Australia (Thwaites and Slater 2000). This is the case for most regions of Australia except for South Australia, where soil and land use survey have been more or less ongoing since the 1940's (Stephens, Crocker et al. 1941). These early surveys formed the basis for the current South Australian site quality classification system (Lewis, Keeves and Leech 1976). In New South Wales, Turvey and Poutsma (1980) developed a soil framework for improving the efficiency of soil-related forestry activities. They describe the mapping of forest soil properties at the plantation compartment-level (20-50 ha) and demonstrate the application of the information to improving a range of silvicultural management decisions, such as forest fertilisation. Detailed forest soil surveys undertaken for similar purposes have also been documented by several authors in Tasmania and Queensland (Table 2.1).

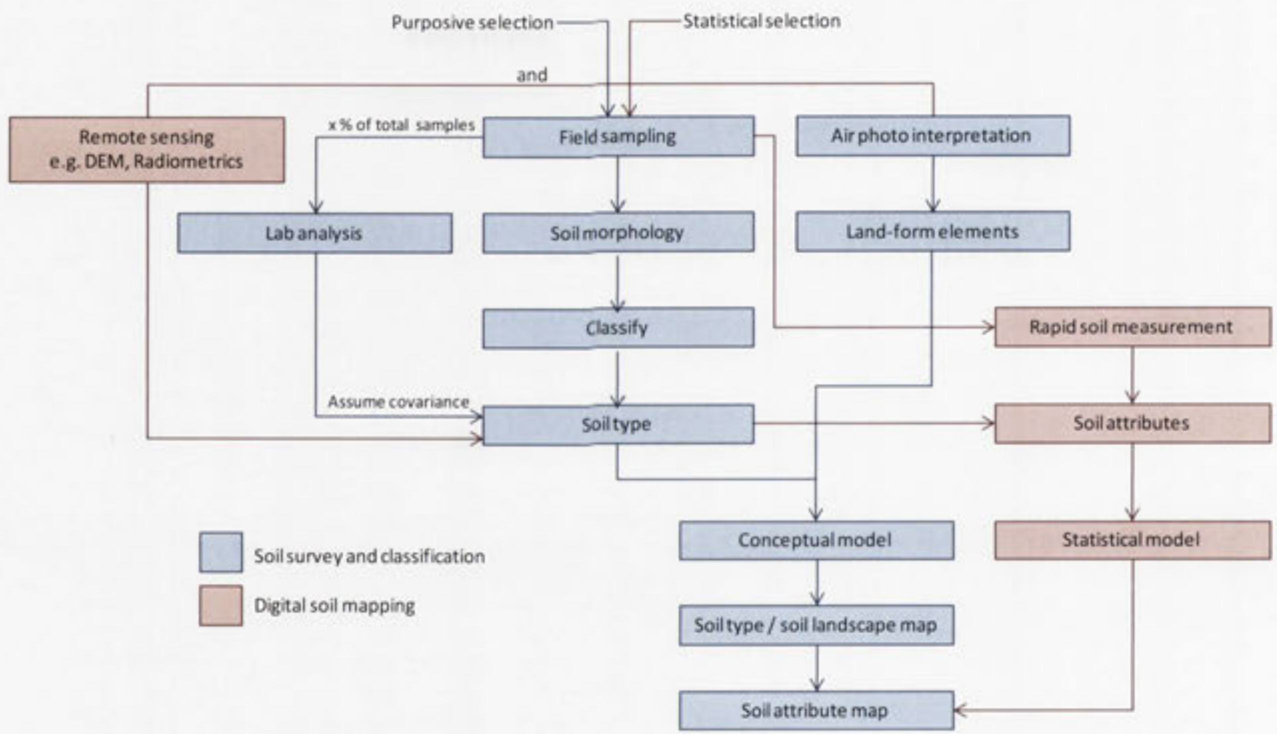


Figure 2.1 Steps in the process of soil survey and mapping. Blue lines denote conventional soil survey and classification and red lines denote steps specific to the digital soil mapping method.

Table 2.1 Summary of compartment-level soil surveys conducted in Australian plantations.

Author/s	Region	Scale of mapping	Extent of map region	Map unit	Main application
Stephens et al. (1941)	Mount Gambier, South Australia	< 1:10 000	170 000 ha	Soil type	Site suitability for *P. radiata*
Lewis et al. (1976)	Mount Gambier, South Australia	< 1:10 000	170 000 ha	Site quality class as determined by soil type and vegetation criteria	Site classification
Turvey and Poutsma (1980); Turvey (1980)	Gippsland, Victoria	1:25 000	40 000 ha	Soil type and soil association	Silvicultural management and forest operations
Ross and Thompson (1991)	Gympie, Queensland	< 1: 10 000	40 ha	Soil type	Estimation of productivity
Laffan and Nielson (1997)	Northern Tasmania	1: 50 000 1: 100 000	150 000 ha	Soil profile class, soil association and soil complex	Site classification Planning forest operations and soil management
Ryan and Loughhead (2001)	Southern Hume region, New South Wales	1: 25 000	72 000 ha	Detailed soil profile class (soil chemistry, bulk density and hydraulic data)	Stratification of plantation estates from compartment to regional scales

In situations where detailed forest soil surveys have been conducted, conventional methods of soil survey and mapping which were originally developed for agricultural lands have been employed. However, the forested soil landscape is inherently more complex than agricultural soils. A number of factors restrict the surveyor's ability to sample and map forest soils, particularly at the finer scales. These are typically: the large size and extent of plantation estates, often in the tens of thousands of hectares; difficulty of access; higher degrees of spatial heterogeneity; and forest cover limiting the use of air-photo interpretation to conceptualise soil-landscape relationships. For these reasons, our ability to map fine scale soil variation by conventional methods of soil survey and mapping is relatively constrained.

The ability to integrate aspects of both conventional and quantitative soil survey methods to improve and reduce the cost of soil mapping is a key approach in digital soil mapping methods. Geospatial technologies and quantitative survey methods are used in addition to soil profile data to provide more accurate and precise classification of soil attributes into levels or indexes (e.g. fertility index). Ryan and Loughhead (2001) describe the development of a soil information system based on this approach for managing plantation estates in New South Wales at multiple scales, from the compartment to regional levels. In their work, spatial predictions of key soil properties important to forest management, such as fertility, soil profile depth, effective rooting depth and estimated plant available water holding capacity were generated from a 1:100 000 soil-landscape coverage and existing soil profile data. The soil attribute information was linked to a digital elevation model to increase map resolution to the compartment scale (1:25 000). The use of detailed environmental data in this case reduced field sampling by enabling the spatial extrapolation of fewer, but more detailed soil observations (Ryan and Loughhead 2001).

2.4.4 Summary

As outlined in the sections above, the importance of soil information for forest management is clear, as is the potential application of soils information as a framework for improved forest management decision making. However, the shift towards precision forestry and more intensive production has renewed the need to accurately map the spatial distribution of forest soil properties on a much finer scale than has previously been accomplished. Conventional and quantitative approaches to mapping soil properties are highly developed, but both approaches are constrained to varying degrees by the limitations of soil sampling and measurement, particularly at the finer scales.

2.5 Forest management, soil properties and tree growth

As commercial plantations have been established over large areas, climate, terrain and soil conditions often vary widely within a single plantation estate. The stratification of plantation land into site productivity classes assists in the application of the most suitable silvicultural and management procedures to optimise production on each class of land and enable more precise estimation of product yield (Shepherd 1986). The characteristics of each class must be defined to enable any area to be classified or ranked. The concepts of site, site quality and site productivity are all used in forest management for this purpose.

These terms have been variously defined in the literature and thus require clarification. In brief, the term 'site' refers to an area or geographic location considered to be relatively homogenous in terms of its physical and biological environment and in its capacity to produce above ground wood volume (Grey 1980). Skovsgaard and Vanclay (2008) note that the terms 'site quality' and 'site productivity' are often used interchangeably, although they are not synonymous. They define 'site quality' as referring to the combination of physical and biological factors characterising a particular site, which may involve qualitative description, and 'site productivity' as the quantitative estimate of the potential of a site to produce plant biomass. Site productivity may be expressed as site index (SI), mean annual increment or some other measure of stand characteristics. Site index refers to the height based on a stand at a predetermined age and is the most commonly used expression of forest site productivity (Hagglund 1977).

There are various methods used for estimating site quality. These may be divided into those which measure some characteristics of the tree stand that are considered expressive of site quality, such as tree height, and those which measure one or more of the individual site factors considered to be closely associated with tree growth (Husch, Beers and Kershaw 2003). It is this latter approach to site quality evaluation that has provided the impetus for the considerable attention given to establishing relationships between tree growth and soil properties.

Numerous authors have related site index or other expressions of site productivity to site factors (Rennie 1963; Hagglund 1977). The environmental factors of a site used as criterion for site evaluation can be grouped as climatic (temperature, rainfall, light, wind), topographic (slope, aspect), competitive (other trees and vegetation) and edaphic (soil depth, texture, nutrients, moisture, drainage). Climatic variables are generally used for broad scale qualitative classification of forest areas and are the most appropriate for determining broad areas of land suitability for planting, rather than for more detailed, quantitative classification of stands (Romanyà and Vallejo 2004). Topographic factors and ground vegetation patterns have been employed as indicators of site quality within climatic strata, but for determination of site qualities at yet finer scales within a plantation compartment, factors of the soil are the most useful (Pritchett and Fisher 1987). For this reason, and as many environmental factors are integrated in the soil, a substantial amount of research has been devoted to establishing relationships between soil properties and site index or other expressions of site productivity (Jackson 1965; Jackson and Gifford 1974).

Attempts to use soil characteristics as an index of productivity for even-aged forests are often complicated by the work involved in identifying the most important soil properties influencing growth for a particular species and forest (Watt, Davis et al. 2008); and the complex nature of the relationship between tree growth and soil properties. These are in turn influenced by interactions with other factors of the environment. However, research has established many good correlations between soil characteristics and indexes of site. In his review of soil-site studies, Coile (1952) concludes that the soil properties most frequently related to site index are those that describe the volume of soil available for tree root exploration, the storage capacity of this volume and the availability of water and nutrients within this volume.

Therefore, the soil properties most frequently correlated with growth are soil depth and texture (Coile 1952). In combination, they express growing space, nutrient status and water holding capacity. Effective soil depth is of principle importance as it indicates both the overall volume and supply of available water and nutrients, and the growing space available for tree roots. The effective depth of soil is defined by the depth to a layer which impedes or limits root penetration. This may be due to the occurrence of bedrock near the soil surface, the position of the water table, a less permeable layer, such as a heavy clay, or an impervious stratum, such as a highly developed hardpan. A range of different measures of effective soil depth have been found to be significantly correlated with site quality. The most significant relationships are those with depth of the A horizon above a compact subsoil, depth to the least permeable layer, the depth to mottling (indicative of the depth to restricted drainage and aeration), and the thickness of the soil layer over bedrock (Raupach 1967; Carmean 1975). All these measures quantify the effective rooting depth of trees.

Soil depth and texture properties are most closely related to productivity in cases where soils are relatively shallow and generally fertile. In such cases, site quality typically increases with increasing effective soil depth (Carmean 1975). The relationship is often reported to be curvilinear, whereby small increases in depth can produce large increases in site quality (Pegg 1967). The effect is most significant in shallow soils where depth is defined by the presence of a restricting layer; but is relatively insignificant where soils are very deep and downward root development is unimpeded. The influence of effective soil depth may be further enhanced within a plantation forest by the effect of competition between adjacent trees for soil volume (Jackson and Gifford 1974).

Given sufficient growing space for root development, the features of the soil profile that affect soil water, drainage and aeration become the most important (or limiting), as these influence the availability of water and nutrient supplies (Raupach 1967). Soil-water and aeration relationships are governed mostly by the texture and structural properties of the soil as determined by its parent material and the physical composition of rock, sand, silt, clay and organic matter (Jackson and Gifford 1974). Soil texture variables are also closely related to effective soil depth and physiographic factors. The nature of these interactions determines their influence on growth. For example, water availability and tree growth generally increases as a function of clay and silt content until a point is reached where air space becomes limiting, after which any additional increase in fine particles produces a decline in growth (Ralston 1964). Physiographic factors, such as slope position and other landform features, are also closely related to the physical properties of soil that govern soil-water and aeration relationships. This is due to the strong association between topography and a range of other important soil properties such as depth of the A horizon, soil texture, stone content, organic matter and nutrient availability (Barnes, Zak et al. 1998). Although nutrient availability is an essential requirement for growth, soil chemical and fertility factors are less often mentioned in soil-site studies as important correlates for growth. This is mainly because nutrient supplies are frequently correlated with other variables used to describe the physical properties of soil associated with effective depth and texture (Ralston 1964).

While studies relating site factors to site index have typically been directed at estimating an average site quality for a plantation compartment, research has also established many significant correlations between soil properties, particularly soil depth variables, and site index; this has enabled determination of site qualities within a compartment. The use of soil factors as criteria for more refined stratification of plantation land into site quality classes is perhaps best exemplified in Australia by the site classification system for South Australian *P. radiata* plantations. Lewis, Keeves and Leech (1976) describe the use of combinations of vegetative and soil factors to evaluate sites for broader scale objectives, such as assessing land for purchase, siting of exotic species, and forecasting productivity; and for finer scale objectives related to planning silvicultural activities, such as determining optimal thinning range and estimating, predicting and regulating yield. Site quality was found to be highly correlated with soil type and depth to a water retentive layer, which when used in combination with tree characteristics (height to green crown, predominant height, maximum tree diameter), provided a practical means of stratifying sites into site quality classes at the plantation compartment level (20-50 ha), with a strata minimum of 0.1 ha (Lewis, Keeves and Leech 1976).

Soil properties are usually related to stand-level measures of tree size, especially measures of tree height, in soil site studies. Indices of height or site index typically refer to stand or mean dominant height (e.g. Pegg 1967; Hagglund 1977; Hunter and Gibson 1984; Grigal 2009). However, variation in individual tree height and other tree characteristics, such as diameter and form within a stand, suggest that the relationship may also be relevant at the level of the individual tree, although this relationship has not traditionally been employed in forestry.

This thesis examines whether variations in attributes of the individual tree are related to local variations in influential or growth-limiting soil properties at that specific site. In which case, measurements of individual tree height, diameter or form, may be useful indicators of local variation in soil properties. The efficiency and cost of a tree-based method for mapping soil properties would depend to a large extent on the simplicity of the tree measurement. It must be more easily and cheaply measured than a direct measurement of soil. However, it may not be the case that the most commonly measured tree attributes are necessarily the most easily measured nor best indicators of soil properties.

Tree height and diameter are routinely measured in a forest inventory as they are used to estimate tree and stand volume and therefore, productivity. However, obtaining accurate and precise measurements of tree height using standard ground-based methods, such as hand-held laser rangefinders, is difficult in closed stands where tree tops are not often easily visible from the ground. Significant differences between hypsometer measurements of the same tree have been reported by a number of authors (e.g. Stone, Turner, et al. (2009), Coops, Wulder et al. (2004)). In their study, Coops, Wulder et al. (2004) reported a mean difference between Vertex hypsometer measurements of approximately 10 % of the mean individual tree height. Measurement of individual tree height can be one of the more time-intensive and expensive components of a forest inventory (Anderson, Reutebuch and Schreuder 2010). Stem diameter (e.g. diameter at breast height) is relatively simple to measure in comparison to tree height. However, the relationship between diameter and soil properties is confounded by the sensitivity of stem diameter to stand density and other factors of site (Kramer and Kozlowski 1960).

Unlike tree height and diameter, the form or shape of the tree stem is not routinely measured. However, it is one of the most important parameters for accurately estimating stem volume and is typically used in an inventory to determine volume tables (Husch, Beers and Kershaw 2003). The shape and taper of tree stems is influenced by both above and below ground resources. The factors which determine stem shape and taper at the base of the stem are the least understood. It is hypothesised that the shape and taper of the butt swell section may be more expressive of variations in soil properties than any other part of the stem. The reasons for this are discussed in the following section.

2.6 The shape and taper of tree stems

The shape and taper of trees may be considered from either a biological or a mensurational perspective. This section is broadly divided into two parts on this basis. In the first part, the patterns of stem shape and taper development and the ways in which these patterns may be modified by environmental or silvicultural practices are discussed in relation to existing theories of stem shape and taper development. The second part of this section considers the way in which the butt swell section has been accounted for in empirical and physiological models of stem shape and taper.

2.6.1 The development of shape and taper in the tree stem

Tree growth occurs from zones of undifferentiated cells known as meristems (Kozlowski 1971). When a tree grows, these undifferentiated cells divide and differentiate into specific types of cells. The lengthening of the tree stem, branches and roots occur from apical meristems, which are the growing points or buds in the tree. Increase in the radial diameter of the tree stem occurs from activity in the lateral meristems. These comprise the vascular cambium which forms a continuous layer around the stem. Cell division within the cambium is stimulated by growth hormones produced in the buds and leaves of the crown. Photosynthetic assimilates produced in the crown are translocated down the stem, resulting in the growth of xylem (wood) and phloem (bark).

The stem shape and taper of excurrent trees follow general laws or patterns of growth that are biologically inherited. Most variations in stem form may be attributed to changes in the size and distribution of the live crown and to the length of the branch free bole (Larson 1963). Carbohydrates and hormonal growth regulators synthesised in the crown determine the amount and type of xylem formed, as well as its distribution along the stem.

In general, stem diameter increases with distance away from the stem apex, reaching a maximum diameter at the base. The tree stem may be divided into three parts– the crown, the clear bole, and the butt swell or base of the stem on the basis of its shape. The shape and taper of each stem segment may be further described in general terms with respect to points of minimum and maximum growth (Larson 1963). Within the crown, diameter growth tends to increase downwards from the apex in relation to the increase in the number of branches. The stem within the active crown usually exhibits a high degree of taper. This downward increase in diameter increment reaches a point of maximum at the base of the live crown or the position of maximum branch development. A corresponding region of minimum diameter increment is often encountered in the clear bole below the crown, but the actual point at which this minimum growth occurs varies according to prevailing growth conditions.

Much of the variation in stem shape and taper may be attributed to differences in height growth; however, the relative distribution of diameter growth along the stem also varies widely with site quality (Larson 1965). Site quality affects the distribution of growth along the bole mainly through its influence on the size and distribution of the crown and the length of the branch-free bole (Larson 1963; 1965). Burkhart and Walton (1985) report that shape and taper generally increase with increasing site index.

While many changes in stem shape and taper development can be considered a function of crown dynamics, many other variables intercede to further modify the distribution of growth along the stem (Kozlowski 1971). Tree growth is determined by the availability of resources such as water, nutrients, and light. Variations in stem shape and taper may be at least partially attributable to differences in site factors such as soil type, depth, fertility and aspect, and climate variables such as rainfall, temperature, light and wind. Silvicultural interventions such as thinning, pruning, fertiliser application and other external influences such as pests, disease and fire, also affect stem shape development (Valinger 1992; Waterworth 2009).

In addition to the aforementioned factors of site, the distribution of maximum diameter growth along the stem changes with height, age, genetics and stocking. In young trees with crowns extending over a greater length of the bole, the point of maximum growth continually shifts upward as the trees mature and crowns recede. The point of maximum growth is usually found at the base of the crown, but this may differ between species. For instance, the maximum has often been reported to be at the mid-point of the crown in long-crowned fir and spruce (Larson 1963). For stand grown trees, Newnham (1965) found that taper increased throughout the life of a tree, but only as long as it maintained dominance within the stand. When a tree became suppressed, growth tended to be more uniformly distributed along the bole, resulting in lower tapers and more cylindrical stem shapes with increasing age. For some species, site index and age have no significant effect on stem taper, such as for Douglas fir (Newnham 1965). The influence of site on stem shape is also reduced for stand-grown trees compared with open-grown trees. Young stand-grown trees share the long crowns and strongly tapering stems typical of open-grown trees but as the stand ages, crown closure initiates natural competition causing the lower branches on the stem to die. The proportion of the stem in the crown produces a progressively longer branch-free bole resulting in trees becoming more cylindrical as stocking increases.

2.6.1.1 Theories of stem shape development

Larson (1963) lists four general theories which aim to explain the physiological development of stem shape and taper in trees. These are the mechanistic, nutritional, water conduction and hormonal theory. Each is summarised below.

Mechanistic Theory To date, the mechanical stress theory has been the most widely supported theory of stem development (Valinger 1992; Osler, West and Downes 1996). The concept that external mechanical stresses alter and modify the shape of the stem has its foundations in the seminal work by Schwendener (1874). Schwendener's (1874) basic ideas were developed into mechanistic laws by Metzger (1893; 1894; 1896) and further modified by Gray (1956). Metzger (1894) identified vertical loading from the weight of the crown and the horizontal loading imposed by the wind as the two types of key mechanical forces acting on the stem. According to this theory, wind forces are considered the dominant factor influencing the shape of the forest tree stem. The stem is viewed as a beam of uniform resistance to bending that is firmly anchored in the soil. Under these conditions, the stem functions as a lever arm and the stress created by the wind on the crown is propagated downward, culminating in a maximum at the stem base. A progressive strengthening of the stem in the form of increased diameter growth parallels the downward increase in stress. If constructed of homogenous material, a beam of uniform resistance to bending would conform to a beam of uniform taper toward the stem base. Metzger was able to demonstrate that stems conformed to this hypothetical beam in branch-free sections of the stem by plotting the cubed diameter against height along the stem, which produces a stem conforming to the dimensions of a truncated cubic paraboloid (d^3/h, where d = diameter, h = height from the stem base). Gray (1956) further developed this work, demonstrating that because the tree is not actually firmly anchored in the soil, the dimensions of a quadratic paraboloid (d^2/h) would be more consistent with the mechanical requirements of the tree.

Nutritional Theory The nutritional theory was first proposed by Hartig (1883) and further developed in subsequent publications (Hartig 1891; 1897; 1901). Hartig hypothesised that the amount of conductive tissue or earlywood in the stem was determined by the rates of transpiration and assimilation. Based on this, nutritional large-crowned trees with high transpirational requirements have strongly tapered stems with a high proportion of earlywood; while, smaller or suppressed trees with small crowns and lower transpiration rates would be less tapered as they form little or no earlywood in the lower bole. Hence, the amount of earlywood formed is determined by the growth conditions that drive transpiration, such as water, nutrients and light. The production of strength tissue in the form of latewood would only commence once sufficient earlywood had been produced to meet transpiration requirements. The nutritional theory makes it possible to predict the effects of silviculture on stem shape by describing the extent to which the change favours transpiration or assimilation. For example, thinning typically increases crown size, which increases transpiration requirements and leads to increasing taper and higher proportions of earlywood. Conversely, pruning decreases crown size and transpiration, resulting in decreasing taper and a decline in earlywood proportions.

Water Conduction Theory The water conduction theory was proposed by Pressler (1864), with further development by Jaccard (1913), Huber (1928) and Waring, Schroeder et al. (1982). The water conduction theory is similar to the nutritional theory but considers the water transport demands of the tree from a functional perspective, rather than a physiological one. For transpiration and photosynthesis to take place, the tree must obtain water from the soil and transport it up through the stem to the crown. The water conduction theory proposes that the shape of the stem is optimised to maximise the transport of water from the roots to the crown. From this perspective, stem shape is related to the size and development of the crown and the roots. More cylindrical stem shapes are produced when there is equilibrium of water transport between the crown and roots. The theory assumes an ideal stem, in which the cross sectional area of the stem between the roots and crown base is of equal size to afford uniformly equal passage for water. The change in stem shape observed within the crown is explained by the progressive reduction in water circulation from the crown base to the top with decline in branch numbers.

Hormonal theory Numerous experiments in the late 1800's and 1900's on the effects of hormones on cambial activity resulted in the hormonal theory of stem development. The hormonal theory is not a specific theory in itself, but provides a physiological basis for the development of stem shape. Tree growth is regulated by hormones (auxins). Hormones produced in the crown and apical meristem are transported down through the vascular system, activating the cambium to produce diameter growth. Many studies have shown that even where assimilates are available in sufficient quantities for growth, activation of the cambium will not take place unless initiated by auxins distributed from the crown (Onaka 1950; Fraser 1952; Wareing 1958). Gradients of hormones regulate the distribution of growth at different points along the stem, which determines stem shape.

Of all the theories described by Larson (1963), the hormonal theory has the strongest basis in tree physiology (Waterworth 2009). As hormones primarily carry out regulatory functions, the hormonal theory on its own cannot sufficiently explain all changes in stem shape and taper observed; but the theory may be considered as adjunct or supplementary to the other stem development theories. Studies of plant growth hormones have consistently shown that nutritional gradients alone, as suggested by the nutritional theory, cannot serve the required regulatory function for stem growth, while the mechanistic and water conduction theories describe the functional requirements of the stem rather than the physiological drivers of cambial activity and distribution of growth along the stem.

2.6.1.2 Summary of stem development theories

As reviewed by Larson (1963), the physiological theories of stem shape development describe how the stem develops and the ways in which different factors and growth conditions affect stem shape. As tree growth is the result of many different functions and physiological processes, none of these theories are mutually exclusive. Each theory clarifies a different aspect of stem function and development. Sufficient assimilate must be supplied to the cambium for stem growth, while hormones control cambial activity and regulate the distribution of this growth along the stem. Trees must also grow in a way to survive and adapt to the effects of wind and gravity, and meet the requirement for sufficient vascular area to transport water, nutrients and assimilates to different parts of the stem.

2.6.2 The development of the stem in the butt swell section

Trees of many species growing in a wide variety of environments often exhibit a shape at the base of the stem that differs from that described above. Depending on the species, this may manifest in the form of a broadened root collar, buttressed base, or elongated butt swell extending several metres up the stem. Butt swell is the characteristic form of basal growth observed in *Pinus* species (Waring, Schroeder and Oren 1982; Rojo, Perales et al. 2005). The literature on stem shape development recognises that shape in the base of the stem differs from that of the main stem, but no simple formula has been derived for the butt swell. Most empirical models of stem taper are unable to account for the butt swell. Models which include the butt swell tend to be highly complex or are developed as segmented models that separate the butt from the rest of the stem (Max and Burkhart 1976; Nagashima and Kawata 1994). Likewise, no single physiological theory has been able to consistently account for all variations in the shape of the butt swell observed (Gray 1956). Site, age and tree height do not have a regular or consistent influence on the extent and shape in this section of the stem (Larson 1963).

The factor most frequently related to the extent of butt swell is the size and length of the crown. However, shape in this section of the stem is the result of a complex of factors. In general, variation in the shape of the butt swell depends on species (Muhairwe 1994), the weight of the stem and crown (West, Jackett and Sykes 1989), effective depth and texture of the soil (Varnell 1998), type of root development (Fayle 1975) and wind (Larson 1965; Osawa 1993; Morgan and Cannell 1994). All these factors influence the shape of the butt swell. The number of factors involved and the complexity of their interactions have thus far precluded attempts to quantify stem shape in this section. Furthermore, quantification of shape in the butt swell has typically attracted less interest in the past as this section of the stem does not comprise merchantable volume and thus has not been of commercial value.

The literature focussing specifically on the butt swell in forest trees is sparse. Explanations for the structure and function of the butt swell have mostly been borne out of work conducted in the late 1800's and early to mid 1900's, as reviewed by Larson (1963). The butt swell has been related in some cases to a strengthening of the lower stem, while in others to the root system and anchoring of the tree (Larson 1963). Since trees are not firmly anchored in the soil, Gray (1956) proposed that increased growth near the base of the stem would confer the additional strength required to resist external forces. Both lateral wind forces and the compressive force exerted by the weight of the stem and crown increase toward the stem base, as per the mechanistic theory. Therefore, theoretically, stand grown trees, particularly those of lesser stem diameter classes, require less strengthening and tend to be more cylindrical. The movement of a large crown contributes substantially to the bending moment of the stem, which reaches a maximum at the base. This may partially account for butt swell as cambial growth tends to be greatest in regions of highest stress. The root system and tree anchorage has also been shown to contribute to the bending moment of the stem. However, in a glasshouse experiment on *Eucalyptus regnans* seedlings, Osler, West et al. (1996) showed that both bent and unbent trees developed a butt swell, concluding that the development of butt swell was independent of the bending stress applied.

In their reviews, Larson (1963) and Gray (1956) hypothesise that trees not deeply rooted in the soil must also be broader at the base; thus, shallow rooted species would possess more pronounced butt swell than deep rooted species. The more extensive work concerning the structure and function of buttressing in tropical forest trees has often been drawn upon in support of this hypothesis. By providing a base which covers a greater area for a given volume, buttressing provides increased support and anchorage, particularly in habitats where the ground provides a weak anchor due to shallowness, texture or moisture content of the soil. The only common factor of environment reported to consistently contribute to the buttressed condition in forest trees is soil depth (Davis and Richards 1934). In their study of forest trees in British Guiana, Davis and Richards (1934) reported a relationship between the occurrence of buttressing and soil type; buttressing was observed in trees on damp shallow soils but no buttressing was observed in trees of the same species types on deep sandy soils. Varnell (1998) also noted a relationship between the extent of buttressing and the degree of water inundation in bald cypress trees growing in floodplains. In a recent study of the buttress form of the rainforest tree species *Microberlinia bisulcata*, Newbery, Schwan et al. (2009) advanced that in addition to the primary structural role of buttresses for large tropical trees, the shape of the buttress also appears to play an important secondary role in aiding nutrient acquisition, especially in low-nutrient soils.

The extent of the root system and anchorage, have also been related to the conditions of exposure during early development. Open-grown trees tend to be more firmly anchored in the soil because they are exposed to increased wind during development. As stand grown trees are relatively unexposed to wind forces during early development, they may be more susceptible to windthrow under high wind conditions or where neighbouring trees have been removed. On the other hand, the support provided by the touching crowns of neighbouring trees can also limit damage by wind forces (Coutts and Grace 1995).

Physiological explanations for the development of shape in the butt swell section examine requirements for the transport of nutrients, assimilate or water between the conductive systems of the stem and that of the conjoining roots. The nutritional theory suggests that the change in direction of the conducting elements between the stem base and root crown impeded the flow of assimilate, necessitating greater growth in the region of the stem near the base for the translocation of nutrients. Although a more functional concept, the water conduction theory explains the butt swell section by comparing the tree vascular system to that of a capillary system. As water flow is reduced in an inclined capillary system, additional growth would be required to compensate for the curvature and inflection of the conductive system in that section of the stem conjoining with that of the tree roots.

2.6.3 Definitions of stem shape and taper

As discussed above, many factors influence the distribution of growth along the stem to determine the stem shape. Measurements of stem shape are therefore the integrated expression of the effects of all these factors. Stem shape is determined by the way the stem tapers. Stem taper can be defined as the decrease in diameter of a tree stem from base to tip or the change in diameter per unit length between any two points along a tree stem (Schreuder, Gregoire and Wood 1993). Variations in stem shape are therefore the result of changes in height and diameter. The terms shape, form and taper have often been used interchangeably to describe the change in diameter with distance along the stem. Gray (1956) distinguishes between these terms, defining form or shape as the characteristic shape of a solid and taper as the rate of narrowing in diameter in relation to increase in height of a given shape or form. Gray's definitions of shape and taper will be used in this thesis. The shape of a geometric solid of regular outline can be described by the values of shape (b) and rate (k) in the expression (Grosenbaugh 1966):

$$y^2 = k * x^b$$

where y is the diameter over bark at breast height, x is the total height of the tree, b is the stem shape and k is the stem taper. The value of b determines the way the solid tapers or its shape and the value of k determines the taper within that shape. Two-dimensional representations of the characteristic types of stem shape are illustrated in Figure 2.2 below.

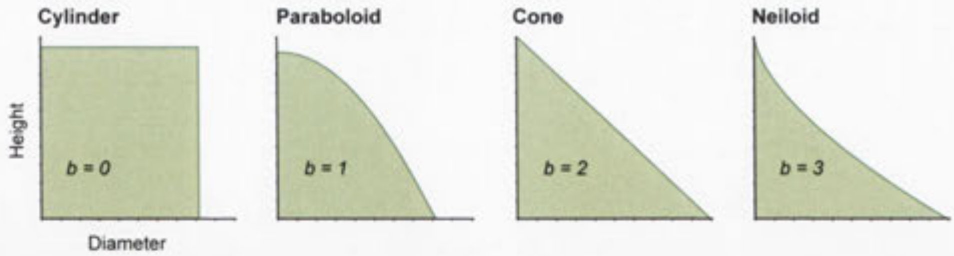


Figure 2.2 Schematic illustration of characteristic stem shapes and their corresponding b values. Adapted from Brack and Wood (1996).

The term stem profile is used to describe the actual shape of the stem along its entire length. A single tree stem may be simply represented by a composite of truncated geometrical solids of different profiles. The frustums of three different solids joined end to end provides the simplest description of the average mature plantation-grown conifer tree, which is typified by a well-defined trunk and small lateral branches (Husch, Beers and Kershaw 2003). In general, the portion of the stem within the crown resembles a cone, the shape of the mid-section approaches the frustum of a paraboloid and the region of the butt swell resembles the frustum of a neiloid (Figure 2.3). The shape of the stem within each of these segments can also vary between these three characteristic shapes.

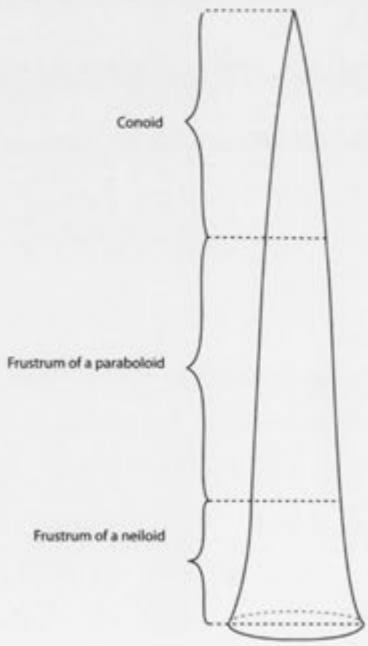


Figure 2.3 Schematic illustration of the characteristic geometric shapes assumed by sections of the tree stem. Adapted from Musk (2006).

2.6.3.1 *Definition of the butt swell section*

Defining the occurrence and extent of the butt swell section has often caused confusion in the literature as trees often have gradually tapering butt swell that extends up the clear bole. No standard definition of the length of the butt swell section is evident from the literature, but there is recognition that it varies with species and is often proportional to height as per truncated taper equations or Grey's line of taper methods. In this thesis, the butt swell section was arbitrarily defined as the bottom 2 m of the stem in mature trees. This length was judged to be adequate to encompass the extent of any butt swell in Australian pine plantation species.

2.6.4 Models of stem shape and taper

The shape of the stem is of primary importance in estimating wood volume and determining product recovery rates in production forestry. A substantial body of research over the past 100 years has been dedicated to developing models that accurately describe stem shape and taper. Two distinct approaches have been followed in developing these models. The first is the empirical approach, which use detailed measurements of diameter along the stem collected from numerous individual trees to develop taper equations. These equations are used to estimate stem shape in other trees from more simple measures such as diameter at breast height. Empirical methods are most commonly used in forest inventory because they are accurate and easily developed. Empirical models also have a known accuracy, provided the conditions under which the models are applied are the same as those under which the model was calibrated (Bossel 1991).

The second is the physiological or process-based approach, which is based on theories of stem shape development. Physiological models are considered to be more general and applicable across sites than empirical models but are usually not as accurate and require large amounts of data. However, for the reasons discussed in Section 2.6.2, neither empirical nor process-based models are able to accurately describe shape in the butt swell section of the stem. The poor performance of models in estimating the shape of the butt swell section is often acknowledged (Kozak 1988; Candy 1989; Courbet and Houllier 2002), but generally dismissed in mainstream forest management related work because it is of little practical use in estimating merchantable or useable tree volume, which is determined from above stump height.

In empirical approaches, the stem profile is plotted as a compound curve with two major inflection points – the first near the ground above the region of the butt swell and the second near the crown. Three families of stem taper models describing this pattern have been developed: single taper models which describe the change of tree diameter from base to tip using a single equation with set variables and exponents (Kozak, Munro and Smith 1969), segmented taper models which use different sub-equations for the various parts of the stem (Max and Burkhart 1976; Kozak 1988), and variable form taper models which use a single equation but where variables or exponents vary with height (Candy 1989). Each of these model families estimate the shape of the butt swell section in different ways.

Single taper models generally lack the flexibility to adequately describe the change in shape and taper observed in the butt swell section (Ormerod 1973). Variable-form and segmented taper models offer a greater degree of flexibility by accounting for the neiloid, paraboloid, and conic forms that typically make up the stem profile from base to tip (Kozak, Munro and Smith 1969; Lee, Seo et al. 2003). Segmented taper models divide the stem into sections and apply a different equation to each section. Max and Burkhart (1976) describe a segmented taper model that accounts for the increased allocation of growth in the butt swell section by using a quadratic submodel for the base section of the tree. Variable-form taper models assume that stem shape varies continuously along the height of the stem and can be very complex in some cases (Max and Burkhart 1976; Kozak and Smith 1993). In their work on *P. radiata* in New South Wales, Bi and Long (2001) demonstrate the greater flexibility and predictive performance of a trigonometric variable-form taper equation over compatible polynomial taper functions for depicting changes in stem shape and taper along the stem and for modelling trees of different sizes. Variable-form and segments taper modelling approaches have been shown to be more general and flexible than single taper equations. These models have been reported to perform well in the butt swell or lower stem section (e.g. Bi and Long 2001). However, in these studies, the butt swell section refers to the lower stem segment but excludes the very base of the stem; measurements are usually taken from 0.1 m or 0.3 m or greater above ground.

While empirical methods are primarily descriptive in nature, physiological models enable greater understanding of the interactions between plant growth and the environment. Physiological models typically predict total growth and then estimate stem growth by attributing a proportion of this total growth to the stem (Waterworth 2009). While few models have attempted to then distribute stem growth along the stem to obtain estimates of stem shape and taper, it is possible to use models to allocate carbon along the stem to provide an estimate of stem shape based on theories of stem development. The theoretical model that has been most commonly implemented inside physiological growth models is water conduction, in the form the pipe model (e.g. Valentine and Makela 2005). The pipe model considers the stem as a set of 'pipes' that connect the foliage of the crown to the root system, providing transport for water and mechanical support (Shinozaki, Yoda et al. 1964). The pipe model is based on the relationship between crown size (expressed as leaf area index), sapwood area and the conversion of sapwood to heartwood over time. To transport water to the crown, trees require a certain surface area of sapwood per unit of foliage mass or leaf area. Although the pipe model is capable of modelling a range of tree shapes and has been widely applied, it does not account for shape in the butt swell (Valentine and Makela 2005).

Recently, Waterworth (2009) developed a model of stem dynamics based on the concept of the 'greedy cell', which combines the hormonal theory of stem growth, the effects of climate and site on the cambium and the flow of assimilate from the crown down through the stem. The greedy cell concept examines the way cambial growth is allocated at different points along the stem based on the flow of assimilates and hormones from the crown down through the stem. As the assimilate passes each cell, the cell utilises as much assimilate as it can, leaving any excess to be utilised by the cells beneath. The total sum of growth along the stem within a year will depend on the availability of assimilate which is influenced by assimilation and the requirements of other parts of the tree, such as foliage and fine roots. The shape of the stem as determined by the allocation of growth at different points along the stem therefore relies on the rate at which the cambium can utilise the available assimilate and the growth conditions and physiological requirements of the tree as a whole (Waterworth 2009). Hence, the model is both source and sink limited. The model developed was able to represent growth and shape along the stem with a reasonable degree of accuracy down to a height of about 0.9 m, but as there were no measurements below this height, stem shape below this point had to be assumed. As trees were 10 - 15 years of age at the time of measurement, no obvious butt swell was observed (Waterworth 2009).

The greedy cell concept however, may provide a useful physiological basis on which to further our understanding of the development of stem shape and taper in the butt. Based on this theory, if the original pool of above-ground resources were large, a substantial portion would accumulate at the base of the tree where growth could proceed relatively unconstrained, leading to a relatively neiloid shape and a higher tapers. Conversely, if there was only a relatively small green crown and limited assimilates being produced, growth in the base of the tree would be slow relative to the upper stem, causing the shape of the stem at the base to be more parabolic with smaller tapers. As the greedy cell concept is driven by canopy dynamics, any deviation from this expected pattern of growth allocation to the base of the stem may suggest that growth in the butt swell section is not driven by the availability of assimilate from the crown.

2.7 Synthesis

As is evident from this review, the history of plantation forestry is characterised by forest managers and researchers seeking to better understand the relationship between tree growth and site and soil characteristics. Now, the economic and environmental benefits of precision forestry have renewed interest in understanding this relationship at a much finer scale, which in turn requires a detailed understanding of spatial variation in soil properties. Conventional and digital methods of mapping soil properties are well developed, but both these approaches are limited by the expense and practical constraints of soil sampling and measurement, particularly at the finer scales. Hence, mapping fine-scale spatial variation in soil attributes important to forest managers cheaply and efficiently requires an alternative approach to soil mapping that minimises or potentially eliminates the reliance on direct soil sampling.

As a result of considerable research investment over the last century of plantation forestry, many useful correlations between soil properties and measures of tree growth have been established. Although soil properties have traditionally been used in soil-site research to predict tree performance, the research suggests that the relationship may also apply in the converse direction; characteristics of the individual tree may be useful predictors of local variation in soil properties.

Collecting more detailed tree stem measurements would be less expensive and labour intensive than collecting more detailed soil measurements to provide the same level of information. Given the long recognised relationship between stand height and site quality, establishing a relationship between individual tree height and soil properties might be the most likely choice. However, the utility of tree height as a predictor of soil properties is restricted by difficulty obtaining an accurate measurement.

Stem shape and taper in the base of the stem may present a more easily measured alternative. Even though a relationship between soil properties and stem shape in the butt swell section of the stem has not previously been established or quantified, physiological theories of stem shape development suggest that the soil resource may exert a greater influence over shape in this section of the stem than any other part of the stem. The extent of growth in the butt swell section of the stem has been often associated with the depth of the soil resource. For plantation grown trees, tree roots may exploit an area up to 10 m around the tree thus integrating soils information within a 10 m radius. On this basis, tree-based indices such as tree shape, taper and individual tree height have the potential to provide soils information at a very fine scale, in the order of 10 m or 0.03 ha, based on the extent of exploitable volume by tree roots.

Chapter 3: Study approach, site descriptions and general methods

3.1 Overview

This chapter describes the biophysical characteristics of each case study region and provides a general description of the research methods used for field sampling, data collection and data analysis. The biophysical descriptions of each study site and descriptions of those methods specific to individual case studies are included within the relevant chapters.

3.2 Study approach

Research was conducted in a series of five stages, progressing from the more simple research questions to the more complex (Table 3.1). Each stage of work was conducted in a different plantation growing region. Together, these regions represent a diverse range of climate, site and soil conditions. The selection of these study regions was partially dependent on the availability of data and data collection possibilities.

The primary aim of the first stage of work was to establish whether changes in soil depth were being expressed in the base of the tree stem by changes in stem shape and taper. To investigate this topic, sampling was conducted in the Australian Capital Territory (ACT) and Tasmania (TAS). Once the possibility of a relationship was confirmed by this initial study, work was extended to a range of case study sites located in several major softwood plantation regions in south-eastern Australia – South Australia (SA) and New South Wales (NSW) – and in southern Queensland (QLD).

As the relationship between tree height and soil depth is well established at the stand-level, the relationship between individual tree height and soil depth was investigated alongside stem shape and taper for each stage of work to provide a point of comparison. The accumulation of data with the completion of each stage of work was used to improve models incrementally. Early 'proof of concept' models describe the relationship between stem shape and soil depth class. Models for estimating absolute soil depth were developed in subsequent stages of the work. The potential to extend these models to a different plantation species and develop more complex models for predicting a range of other soil properties, such as soil nutrients and moisture variables, were also explored as research progressed. In the final stage of work, the model for predicting absolute soil depth from stem shape and taper was calibrated and applied to mapping fine-scale spatial variation in soil depth across a 200 ha plantation area in southern Queensland.

Table 3.1 Summary of key research questions.

Stage of work		Research question/s	Datasets (Species)	Chapter/s
1.	Pilot Study	Is there a relationship between stem shape and taper in the butt swell section and soil depth for *P. radiata*?	ACT, TAS *(P. radiata)*	4
2.	Model development	2.1 Is the relationship general and consistent across a range of site conditions and soil types for *P. radiata*?	ACT, TAS, SA, NSW (*P. radiata*)	5, 6
		2.2 Can absolute soil depth at the individual tree scale be estimated from a calibrated model for *P. radiata*?	SA, NSW *(P. radiata)*	
3.	Model refinement	Is soil depth a simple index for more complex soil resources and can these other relationships with stem shape and taper be quantified?	NSW *(P. radiata)*	6
4.	Model extension	Is the relationship with soil depth generalisable to other *Pinus* species?	QLD (*Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis*)	7
5.	Model testing and application	How does a tree-based model of mapping soil depth variation compare to the conventional method of extrapolation from soil observations alone?	QLD (*Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis*)	7

3.3 Biophysical description of study regions

Study sites were located in pine plantation estates in southern and eastern Australia. These were: Kowen and Pierces Creek forests near Canberra in the Australian Capital Territory (ACT); Fentonbury plantation near Hobart in Tasmania; the Mount Burr plantation estate near Mt Gambier in South Australia; Green Hills and Carabost State Forests near Tumut in New South Wales (NSW); and Toolara State Forest near Gympie in southern Queensland (Figure 3.1).

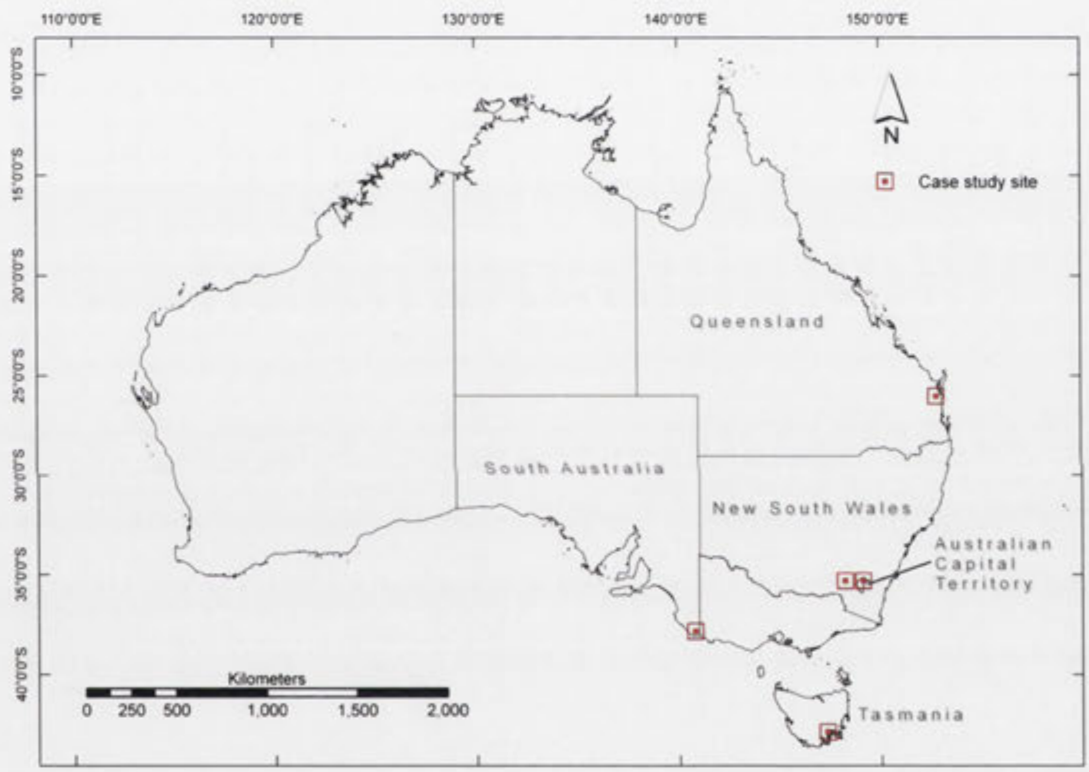


Figure 3.1 Location of study sites in Australia. Sites were located in South Australia, Tasmania, New South Wales, the Australian Capital Territory and in Queensland.

These regions encompass a range of different climate and site conditions (Table 3.2). Of all the study regions, the ACT has the lowest rainfall. ACT plantation soils are typically clayey, water and nutrient limited (primarily nitrogen) and shallow. Hence, sites are prone to summer drought and conditions are generally considered marginal for growth. The Mt. Gambier region is characterised by relatively high rainfall and predominantly sandy soils, overlying limestone bedrock. Soils are typically nutrient poor. The Tasmanian and New South Wales regions have relatively high rainfall and soils are generally nutrient-rich and deep. *P. radiata* is the one of the primary species grown in these regions. The south-east

Queensland region has a humid subtropical climate characterised by humid conditions, with high temperatures and rainfall during summer months, but relatively low temperatures and rainfall during winter months. Soils are nutrient-limited in many areas, particularly in terms of phosphorus. The main plantation species now grown in this region is *Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis* (Queensland hybrid).

Table 3.2 Key biophysical characteristics of ACT, TAS, SA, NSW and QLD study regions.

	ACT	TAS	SA	NSW	QLD
Mean annual rainfall (mm)	686.9	736.3	747	1281.2	1287.6
Mean max. temperature (°C)	19	17.7	18.9	19.6	26.4
Mean min. temperature (°C)	6.5	5.9	8.1	5.5	13.7
Elevation (m)	700	189	63	655	49

Source: Bureau of Meteorology (BoM) weather stations nearest to each case study region (Stromlo Forest, ACT; Bushy Park, TAS; Millicent, SA; Batlow Post Office, NSW; Toolara Forestry, QLD).

3.4 Field sampling

The general methods used for collection of tree and soil data at each case study site are described in the following sections.

3.4.1 Selection of plantation compartments

Plantation compartments were selected on criteria of age class, equivalent thinning history and variability in soil type. Stands in age classes more than 14 years were selected to ensure near maximum root development and full exploitation of soil resources. Unthinned stands were selected where possible to remove the potential influence of stand density. In some regions, such as in South Australia, soil depth varies in concert with soil type. Thus, maps of soil type were used where available to identify compartments with a range of soil types to increase variability in the soil depth data collected.

3.4.2 Sample plots

Two main methods were used for the location of sample plots within plantation compartments. The method chosen depended on the characteristics of the region of interest, availability of environmental data, and site accessibility. In cases where maps of soil type were available, sample plots were positioned at regular intervals along transects which crossed through a number of soil types; where soil type maps were unavailable, slope position (valley bottom, mid-slope and ridge top) were used as selection criteria. The size of each sample plot ranged from 2 to 6 trees depending on the objectives of each stage of work (Figure 3.2). Representative trees – growing away from any gaps in the row (100 % stocking) – were selected where possible. A global positioning system (GPS) was used to record the geographic location of each sample plot.

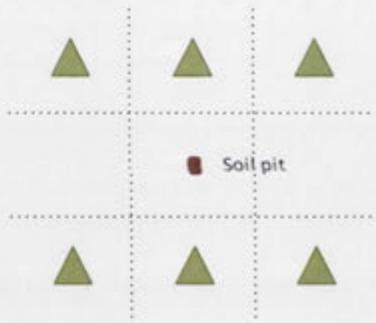


Figure 3.2 Schematic illustration of six tree sample plot.

3.4.3 Measurement of individual tree heights

Total tree height was measured with a hand-held rangefinder (Vertex III, IV and VL402, Haglöf, Sweden) using standard methods (Wood, Turner and Brack 1999). Trees were measured on the uphill side from the base of the stem to apex of the stem. All observations were taken from two independent positions, at a distance from the tree equal to about 1.0 - 1.5 times the approximate height of the tree. As instrument precision is within ± 0.5 m of a 20 m tall tree, the difference between two independent measurements is expected to be less than 1.0 m. Hence, differences of less than 1.0 m between the two measurements were considered acceptable and within instrument precision; if differences were greater than 1.0 m, measurements were checked and trees were remeasured as appropriate.

3.4.4 Measurement of stem shape and taper

The butt swell section of the tree stem was defined in this thesis as the bottom 2 m of the tree stem. Stem shape and taper in the butt swell were estimated by intensive measurement of diameter over bark at selected points along the length of the basal 2 m of the stem, and total tree height (*H*). Diameter over bark measurements were performed using standard methods (Wood, Turner and Brack 1999). Measurements of diameter (*d*) were taken from at least seven heights (*h*) along the stem, at approximately 0.3 m intervals, and included a measurement at the base (0.0 m) and at breast height (1.3 m above ground level). As the actual size of trees also contributes to the overall variation in the data, a method of standardising stem shape and taper estimates between trees of different sizes was required. To adjust for differences in the actual size of trees, diameter and height measurements were converted to relative diameters and relative heights, prior to estimation of shape and taper values. The use of relative height rather than absolute height reduces the extent of error propagation from any inaccurate estimate of tree height. Thus, the impact of any error in tree height on the estimated values of shape and taper is expected to be negligible. Each diameter observation was calculated in relation to diameter at breast height, which was given a reference value of 1.0, while their corresponding heights were calculated in relation to total height, which was given a reference value of 1.0.

Values of shape and taper were estimated using the paired measurements of diameter and height in the basal 2 m of the stem and total tree height in the general equation based on Grosenbaugh (1966):

$$y^2 = k * x^b$$

where $y = \frac{d}{DBH}$, $x = 1 - \frac{h}{H}$, b denotes the shape of the stem relative to DBH and k denotes the stem taper relative to DBH

Although it is recognised that shape and taper are co-related variables, both these variables have been included together in all regression analyses. Including multiple independent variables that are co-related in the same function may influence interpretation of results if the correlation is strong. As regression assumes variables are independent, the estimate of error (precision) may be slightly biased since the assumption of independence has not been completely met. However, because the correlation is weak (e.g. $R^2 = 0.1$ based on QLD data, Appendix 3), there is negligible impact on parameter estimates and conclusions of significance.

3.4.5 Soil assessment and characterisation

Soil can be characterised in terms of many parameters. In this study, the characterisation of soil properties became progressively more detailed as the research moved from the more simple 'proof of concept' objectives to the more complex objectives in later stages of the study.

Different methods of soil assessment and characterisation were employed depending on the aims of each stage of work. In early work where the main goal was proof of concept, soil depth classes were used. Models for predicting depth class were also developed in later stages of work, but these models were exploratory in nature, serving primarily as a basis on which to develop models for predicting absolute depth. Soils were initially divided into either shallow or deep depth classes by visual assessment of environmental indicators. The methods used for soil depth class assessment are described in further detail in Chapters 4 and 5 of this thesis. Absolute soil depths were measured in latter stages of work. In general, soil morphology was assessed and soil depth was measured using a hand auger. In New South Wales (Chapter 6), samples were collected from mechanically excavated soil pits and analysed for a range of other soil physical and chemical properties.

Effective soil depth is defined in this thesis as the depth to a layer which impedes or limits root penetration, as described in Section 2.5. In situations where there was no apparent root-impeding layer, a maximum depth of about 2.0 m was used, given practical limitations. For *P. radiata*, this depth should include more than 90 % of the root zone; although it is acknowledged that in some instances, sinker roots may penetrate below this depth (Davis, Neilsen and McDavitt 1983; Nambiar 1983).

Effective soil depth was used as a surrogate variable for the functional effective soil volume that can be exploited by tree roots. Although the use of soil depth is a crude approximation for soil volume in the context of forest soils, and there are other factors (e.g. coarse fragments, bulk density and soil texture) that define this effective soil volume, soil depth was selected on the basis of the simplicity of its measurement and practicality for addressing the primary objective of this thesis. Ideally, a standardised approach involving comprehensive characterisation of all the soil factors that define effective volume of soil would have been applied for each case study. Since the study approach was incremental and based on an unproven concept, a simpler approach was adopted at the outset and the descriptions of soil evolved as work progressed.

3.5 Data analysis

All data analysis was performed using JMP version 9 (SAS Institute Inc 2010). SPSS version 19 (SPSS Inc 2010) was used to produce some graphical output.

3.5.1 Data exploration

Standard graphical methods were used for data exploration. Histograms and box and whisker plots were used to examine the general characteristics and distribution of the data (centre, spread, skewness, outliers). Scatterplots were used to examine the strength and direction of relationships between soil variables and to identify potential issues, such as nonlinear relationships, non-constant spread and outliers. Two-sided independent sample t-tests were used to test for statistically significant differences between tree attributes and soil depth class. The significance level used for p-values in all analyses was 0.05.

3.5.2 Model development

Regression analysis was used to describe the distribution of soil attribute values as a function of tree variables. Logistic regression, simple linear regression, and linear multiple regression were used to develop models. Models were parameterised by fitting the full factorial model, and removing non-significant parameters and highest order interactions preferentially, until a parsimonious model with all significant ($p < 0.05$) parameters was found. Although backwards stepwise regression models often include more significant parameters than is strictly efficient, it is a more powerful approach to identifying the maximum number of likely important parameters. Predictor variables tested were region, shape, taper and height and have been defined as follows:

Region – a nominal variable, denoting the geographic location of the sample site (Australian Capital Territory (ACT), Tasmania (TAS), South Australia (SA) or Queensland (QLD)). The regional parameter was included in all models fitted with data from more than one sample location. The parameter acts as a proxy for all gross variations in site between sampling locations, such as rainfall, temperature, age, planting and management histories.

Shape (*b*) – denotes relative stem shape in the bottom 2 m of the tree stem (unit-less)

Taper (*k*) – denotes relative taper in the bottom 2 m of the tree stem (cm/m)

Height – denotes individual tree height (m). Individual tree height was tested alongside shape and taper in separate models for each stage of work.

The regional parameter denotes the sample location. Sample locations were not replicated, nor was sampling conducted across climatic gradients (e.g. rainfall); therefore, it is not possible to extrapolate and identify which site variables are significant within the overall 'regional' parameter. It was attempted as far as was practical to use sample sites of similar age and management history, but any unavoidable variations in site would nevertheless be subsumed by the regional parameter.

As depth class is a binary response (shallow or deep) logistic regression was used to develop models for the prediction of depth class. The models describe the probability of shallow soils as a function of tree attribute variables. In the logistic model, explanatory tree attribute variables and regression coefficients describe a function of the mean of soil depth (i.e. probability of a particular depth class) rather than the mean of soil depth itself. Statistics for the logistic regression are summarised in two tables: the specific likelihood-ratio Chi-square (χ^2) test for goodness of fit, referred to as the Whole Model Test in JMP, and the parameter estimates table. The whole model test is analogous to the analysis of variance for a continuous response variable and evaluates whether the model fits the data better than constant response probabilities or the null model (SAS Institute Inc 2010).

The Whole Model Table lists the following quantities: Model, -LogLikelihood, DF, χ^2, Prob $> \chi^2$ and R^2 (U). The negative sum of logs of the observed probabilities or the negative log-likelihood (-LogLikelihood) statistic is a measure of uncertainty analogous to the sum of squares for continuous responses. The -Loglikelihood statistic is reported for each of the Difference (difference between the full and reduced model), Full (includes the intercepts and all effects) and Reduced (only intercepts) models. The χ^2 statistic tests the hypothesis that the model fits no better than the null model. The uncertainty coefficient or R^2 (ratio of the Difference to the Reduced negative log-likelihood values) ranges from 0 (no improvement) to 1 (perfect fit). A nominal logistic model rarely has a high R^2.

The Parameter Estimates Table lists the parameter estimates, standard errors and associated hypothesis test. The nominal logistic model fitting process generates an intercept parameter for each of $k - 1$ dummy variables, where k is the number of response levels. As the Region term is a nominal variable, $k - 1$ variables are generated. For example, where there are four variables (locations) for Region, three dummy variables will be generated during the fitting procedure.

Simple linear regression was used to describe the distribution of soil depth or other soil properties as a function of a single tree attribute variable. Model fit was assessed and assumptions of linearity, constant variance, normality and independence were tested by examining individual scatterplots of response versus predictor variables and plots of residuals versus fitted values (Ramsey and Schafer 2002). Multiple linear regression was used to describe the distribution of soil depth as a function of multiple tree attribute variables. In Chapter 6, it was also used to describe the distribution of a single tree attribute variable as a function of multiple soil attribute variables.

Simple linear and multiple regression statistics are summarised in the Summary of Fit, Analysis of Variance and Parameter Estimates tables. The Summary of Fit table lists the goodness of fit statistics: R^2 value, root mean square error (RMSE) and the total number of observations (n). The Analysis of Variance (ANOVA) table compares the model fit to a simple fit of a single mean or the null model. The table lists the sources of variation (Model, Error and Corrected Total), the degrees of freedom (DF) for each source of variation and the associated sum of squares (SS) and mean sum of squares (MS), and F-test statistics for the hypothesis that the specified model fits no better than the overall response mean. The Parameter Estimates table shows the estimates of the parameters in the linear model and t-test statistics for the hypothesis that each parameter is zero.

For each model the residual plots were examined to ensure that the assumptions of the regression were met. All models were fitted in JMP which uses centred polynomials, which makes the test for the main effect independent of the squared term (SAS Institute Inc 2007). Hence, all parameter estimates and interaction terms are centred by the mean. Main effects are not centred. Tests are consistent and invariant with changes in region.

3.5.3 Model evaluation

Given the small sample size, leaving out too many points as an independent reserve for model evaluation would be impractical. Thus, a resampling procedure was selected for model evaluation. Resampling procedures mimic the use of independent data, but enable the full or most of the data to be used for model development (Vanclay 1994). Cross-validation is a common method of resampling in which each datum is deleted in turn and the model fitted to the remaining n - 1 data (Stone 1974; Snee 1977; Kozak and Kozak 2003). Models were manually cross-validated using this procedure. Results of the cross-validation of the final models derived from the overall dataset are presented in Chapter 6.

3.6 Summary

This study was conducted in a progressive series of stages. Sample sites were located in five major plantation growing regions in south eastern Australia. These were selected to encompass a diversity of climate, site and soil conditions. The selection of study sites and the extent of soil and tree measurement were also partially dependent on the availability of data and practical possibilities for data collection. Individual tree height was explored alongside stem shape and taper as a predictor of soil depth class and absolute soil depth for each stage of work. As described previously, methods used to assess soil depth differed between stages of work as a result of the incremental study approach. Soil depth class was used in preliminary work as a crude proxy for soil depth. Depth class models were developed in cases where depth class was a significant ($p < 0.05$) parameter in a logistic regression. Specific details of methods used for field sampling, data analysis and model development are described within the relevant chapters.

Chapter 4: Establishing the relationship between stem shape and taper in the butt swell and soil depth

4.1 Introduction

As described in Section 2.6.2, the relationship between stem shape and taper in the butt swell section of the stem and soil resources has been implied in the literature, but the relationship has not been established or quantified. Shape and taper in the base of the stem is reported to be the result of a complex of factors, which include both above-ground variables, such as the weight of the stem and crown, and below-ground soil variables, such as effective depth and soil texture. Theories of stem shape suggest that the increased growth allocation to the butt swell section serves mostly a functional purpose and may be attributed to the strengthening of the lower stem, the development of the root system and physical anchoring of the tree. Studies that investigate the associated phenomenon of buttressing in tropical trees have shown that the extent of buttressing is consistently associated with the shallowness of the soil.

In this chapter, the hypothesis that there is a relationship between stem shape and taper in the butt swell section of the stem and effective soil depth was explored. It was theorised that any such relationship would more likely be expressed and detected under conditions where soil resources were the main limiting factor. To investigate this hypothesis, two *P. radiata* plantation sites with soil conditions considered marginal for plantation growth were selected. These were located in the Australian Capital Territory and in Tasmania. Soils at the ACT sites were characterised by relatively shallow, nutrient limited soils, while soils at the Tasmanian site were characterised by relatively deeper, but similarly nutrient limited soils. The specific aims of this case study were:

1) To establish a relationship between stem shape and taper in the butt swell section of the stem and effective soil depth

2) To establish a relationship between individual tree height and effective soil depth

3) To compare the practical use of stem shape and taper with individual tree height for predicting soil properties.

4.2 *Methods*

4.2.1 Location and biophysical descriptions of sample sites

Sample sites were located in *P. radiata* plantations in the ACT and Tasmania (Figure 4.1). In the ACT, sampling was conducted at two sites: Kowen Forest (35.31°S, 149.31°E), located about 15 km east of Canberra and Pierces Creek Forest (35.33°S, 148.92°E), located about 20 km west of Canberra. In Tasmania, sampling was conducted at Fentonbury (42.65°S, 146.77°E), about 70 km north-west of Hobart.

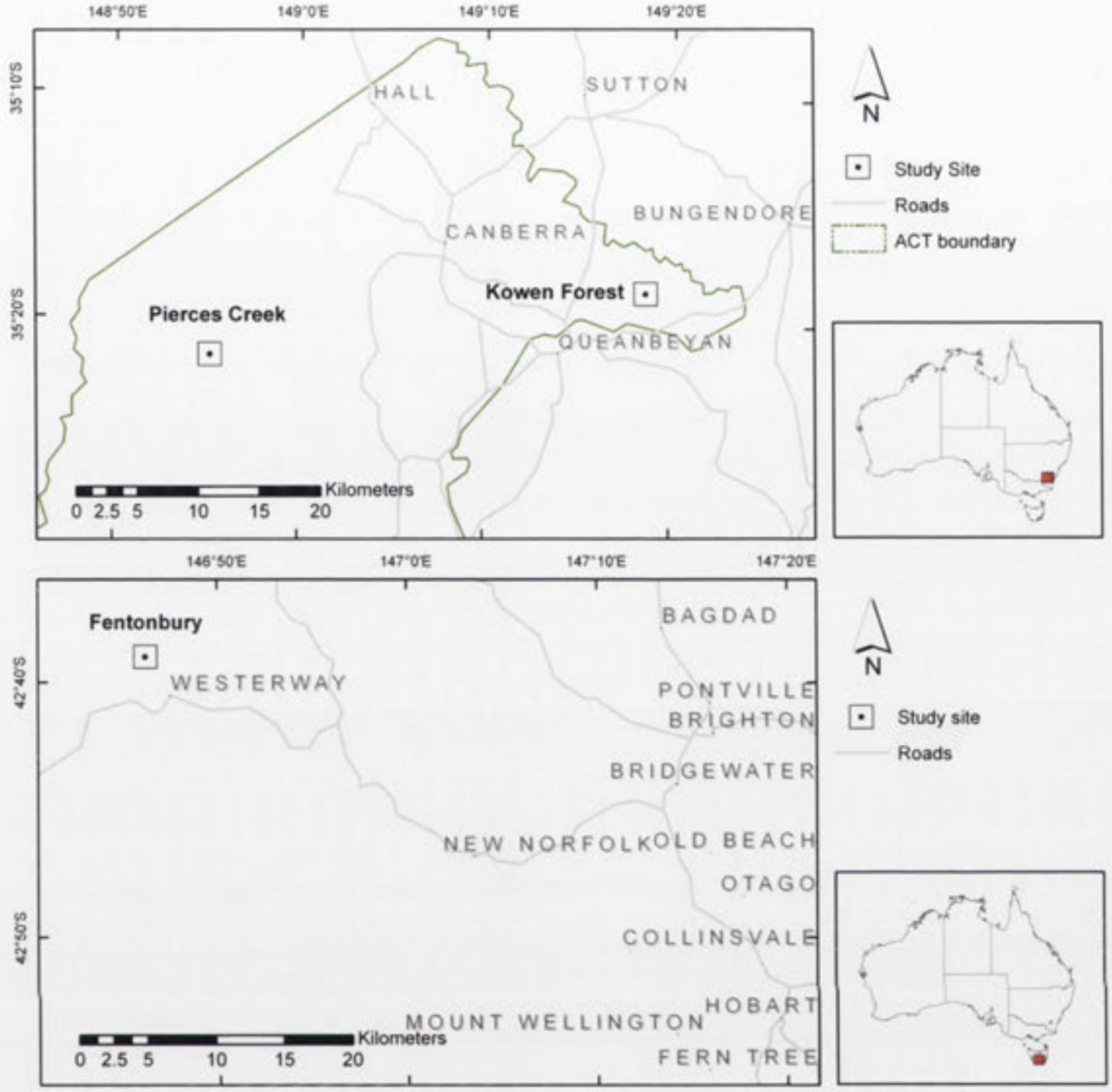


Figure 4.1 Location of Kowen and Pierces Creek in the ACT and Fentonbury in Tasmania.

Climate is similar, on average, across all three plantation estates (Table 4.1). Fentonbury has slightly higher rainfall and cooler temperatures. The soils of the ACT sample sites are both considered to be marginal for *P. radiata* growth. The geology of Kowen is Ordovician metasediments consisting mostly of greywacke, sandstone, chert, limestone and quartzite. Local relief is less than 200 m, and elevation is 578 m above sea level. Soils are shallow (< 0.4 m) well-drained Rudosols on crests and moderately deep (< 1.0 m) well-drained red and yellow Chromosols and/or Kandosols on side slopes. Soils are nutrient-limited (primarily nitrogen), stony, hard-setting and acidic (Jenkins 2000). The geology of Pierces Creek is a combination of Ordovician metasediments and Silurian granite. Local relief is less than 200 m, and elevation is 700 m above sea level. The soils are duplex Chromosols with a pronounced texture contrast between the surface (A) and subsurface (B) horizons. The A horizon is relatively free draining and permeable to a depth of about 0.4 m, but the B horizon has poor permeability and high bulk density, which restricts fine roots to the A horizon. Soils are similarly nutrient limited (primarily nitrogen), stony and acidic (Benson, Landsberg and Borough 1992). The Fentonbury plantation in Tasmania is situated on Triassic sandstone. Soil surface horizons consist of free-draining sandy soils permeable to a depth of about 0.6 m, overlying clayey subsurface horizons of reduced permeability. Deeper soils on lower slopes are well-developed and often have humus iron pans at the surface-subsoil boundary. Soils are moderately well drained to imperfectly drained, and are low in phosphorus and nitrogen throughout. Soils are considered marginally suitable to unsuitable for plantations due to very low site productivity and high erodibility (Grant, Laffan et al. 1995).

Table 4.1 Key biophysical characteristics of Kowen (ACT), Pierces Creek (ACT) and Fentonbury (TAS) sites.

	Kowen	Pierces Creek	Fentonbury
Mean annual rainfall (mm)	652.4	716	736.3
Mean max. temperature (°C)	20.2	20.8	17.7
Mean min. temperature (°C)	7	6.9	5.9
Elevation (m)	695	580	189

Source: BoM weather stations nearest to case study sites (Huntly, NSW; Sutton, NSW; Fentonbury, TAS)

At Pierces Creek and Kowen Forest sites, stands were aged 14 and 15 years respectively at the time of measurement. Stands were unpruned and fully stocked (unthinned). At the Fentonbury site, stands were aged 29 years at the time of measurement. Stands at this site were unpruned and had been thinned. Planting was at 1800 – 2000 stems per hectare, with first thinning in 1997 and second thinning in 2006.

4.2.2 Measurement of soil and trees

In this study, depth class was used as a crude, but easily-assessed proxy for soil depth. Soil depth classes ('shallow' or 'deep') were inferred by observation of site characteristics associated with previous site preparation operations (ripping or subsoiling) and observation of natural landscape or topographic features. At the ACT sites, relative change in depth was determined by walking along a rip-line and observing for the presence of upturned rock brought to the surface during site preparation. Presence of upturned rock would suggest depth to bedrock was less than tine depth and hence, shallower soil at that point. As rip-lines were not evident at the Tasmanian site, soil depth was assessed by topographic position. Soils were deemed shallower on ridge tops and deeper in valley bottoms.

At each sample site, plots of 4 - 6 trees were measured in each depth class (Figure 4.2). Representative trees growing away from any gaps in the rows were selected. Total tree heights and diameters over bark were measured using general methods, as outlined in Section 3.4. Stem shape and taper in the bottom 2 m of the tree were calculated using the general taper function described in Section 3.4.4 .

Figure 4.2 Plots of trees in deep and shallow depth classes were measured at the ACT and TAS sites.

4.2.3 Data exploration and model development

As described in Section 3.5, box plots were used to examine the general distribution of the data and t-tests were used to test for significance ($p < 0.05$) of independent variables. The probability distribution of depth class was described in a logistic regression.

4.3 Results

4.3.1 Data exploration

The average value of the stem shape parameter was greater than 3 for all case study sites (Table 4.2). Mean tapers were similar across all sites, with values ranging from about 1.3 - 1.5 cm/m. Mean individual height of trees was about 13 m at ACT sites and 25.5 m at the Tasmanian site. Stem shape and taper measurements were more precise compared to height measurements. Standard deviations were less than 10 % of the mean value for shape and taper measurements, but greater than 10 % of the mean value for height measurements.

Table 4.2 Mean stem shape and taper in the basal 2 m of the stem, tree height and other sample characteristics at ACT and TAS case study sites. *Bracketed values denote the standard deviation.*

	ACT		TAS
	Kowen	Pierces Creek	Fentonbury
Age (years)*	15	14	29
Thinning	Unthinned	Unthinned	Thinned
Plot size (individual trees)	6	4	6
Sample size (plots)	12	8	12
Mean DBH (cm)	25.1 (3.4)	21.7 (3.4)	32.7 (4.5)
Mean height (m)	13.7 (1.4)	13.05 (1.3)	25.5 (2.7)
Mean stem shape	3.57 (0.81)	3.11 (0.72)	6.71 (0.88)
Mean taper	1.45 (0.13)	1.39 (0.01)	1.47 (0.12)

* at time of measurement

The maximum recorded heights of trees in the deep soil depth class were 1 - 2 m greater than the maximum height of trees in the shallow soil depth class for both ACT sites. At the Tasmanian site, the maximum height of trees in deep soils was at least 5 m greater than the maximum height of trees in shallow soils (Figure 4.3). There was no significant ($p > 0.05$) difference in either shape or taper with change in soil depth class for all sites, but individual tree height was significantly ($p < 0.05$) greater in deep soils than in shallow soils for all sites except for Kowen Forest (Table 4.3).

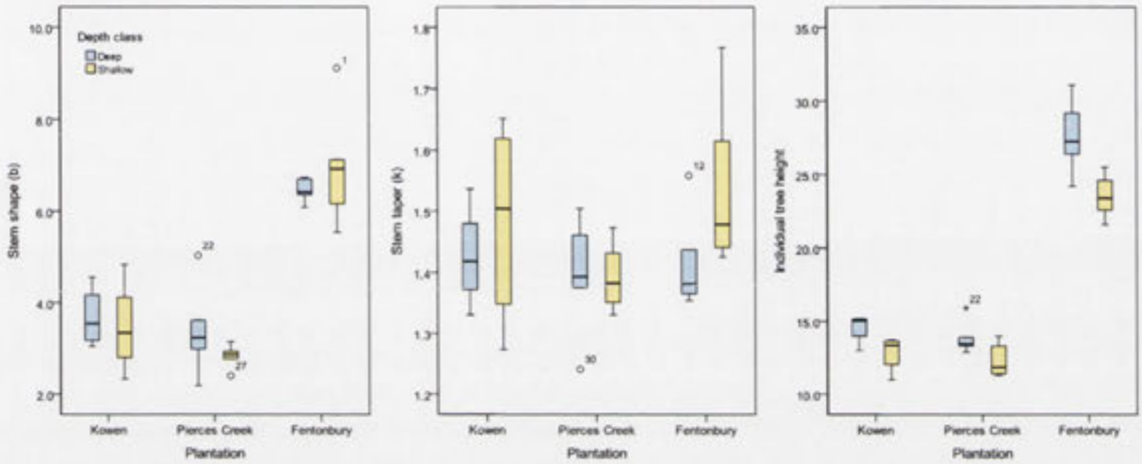


Figure 4.3 Boxplots of stem shape, taper and individual tree height grouped by soil depth class for Kowen, Pierces Creek and Fentonbury sites.

Table 4.3 Differences in stem shape (*b*), taper (*k*) and height with change in soil depth class for Kowen, Pierces Creek and Fentonbury sites.

Plantation	Parameter	Depth class	n	Mean (SE)	*p*-value*	Mean difference	95 % Confidence Interval
Kowen	*b*	Deep	4	3.68 (0.33)	0.74	0.21	[-1.29, 1.72]
		Shallow	4	3.46 (0.52)			
	k	Deep	4	1.43 (0.04)	0.56	-0.06	[-0.29, 0.17]
		Shallow	4	1.48 (0.08)			
	Height	Deep	4	14.57 (0.53)	0.08	1.72	[-0.29, 3.73]
		Shallow	4	12.85 (0.63)			
Pierces Creek	*b*	Deep	6	3.38 (0.38)	0.19	0.55	[-0.33, 1.43]
		Shallow	6	2.83 (0.10)			
	k	Deep	6	1.39 (0.04)	0.95	0.003	[-0.09, 0.09]
		Shallow	6	1.39 (0.02)			
	Height	Deep	6	13.82 (0.44)	0.04	1.53	[0.12, 2.94]
		Shallow	6	12.28 (0.46)			
Fentonbury	*b*	Deep	6	6.45 (0.10)	0.34	-0.51	[-1.64, 0.62]
		Shallow	6	6.96 (0.50)			
	k	Deep	6	1.41 (0.03)	0.08	-0.12	[-0.26, 0.02]
		Shallow	6	1.53 (0.05)			
	Height	Deep	6	27.57 (0.97)	0.005	4.05	[1.55, 6.55]
		Shallow	6	23.52 (0.57)			

**p*-value based on 2-sided independent sample t-test

4.3.2 Model development

Stem shape, taper and height parameter estimates were not significantly different between the two ACT sites, Kowen Forest and Pierces Creek. This might be attributed to the relatively small size of the sample or to the inherent similarities in stand and biophysical characteristics between the two sites. As study sites were not significantly different, data for Kowen Forest and Pierces Creek were grouped together as a single geographical region – ACT. Fentonbury Forest was likewise classed as a region – TAS. ACT and TAS regional parameter estimates were significantly different to each other. There were clear differences in the range and distribution of shape and taper values between the two regions (Figure 4.4).

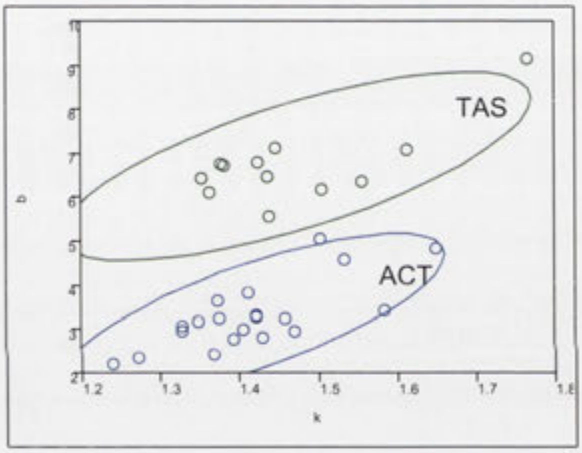


Figure 4.4 Scatterplot of stem shape (b) on stem taper (k) grouped by region for ACT and TAS case study sites.

Individual tree height, stem shape and taper parameters were all significant predictors of soil depth class in a logistic regression. Parameters in the height model were individual tree height and region. Parameters in the stem shape and taper model were shape (b), taper (k) and region (Table 4.4). In this model, the regional parameter estimate was not significant in itself ($p > 0.05$), but appears to act as a proxy for the larger-scale variations in climate and genotypes across regions, reducing the residual error in the model and improving its precision. For this reason, it was retained in the model.

Table 4.4 Logistic regression statistics of depth class on stem shape (*b*) and stem taper (*k*) for ACT and TAS case study sites.

Whole model test

Model	-Log Likelihood	DF	χ^2	$P > \chi^2$
Difference	3.78	3	7.57	0.056
Full	18.4			
Reduced	22.18			

Logit R^2	0.17
Observations	32

Parameter estimates

Coefficient	β	SE β	χ^2	$P > \chi^2$
Intercept	14.04	6.43	4.77	0.03
Region [ACT]	2.44	1.38	3.15	0.08
Region [TAS]	-2.44	.	.	.
b	1.68	0.83	4.06	0.04
k	-15.56	6.41	5.89	0.02

Prediction formula:

$$Prob[Shallow] = \frac{1}{1 + e^{Ln[Deep]}}$$

where $Ln[Deep] = 14.04 + Region + 1.68 * b + (-15.56) * k$

The logistic model shows that deeper soils are associated with decreasing tapers and increasing values of stem shape for both ACT and TAS regions (Figure 4.5). The range of shape values was higher on average for TAS than for ACT. Predicted values of shape ranged from 2 - 6 for ACT and 6 - 8 for TAS. Despite differences in absolute soil depths and values of stem shape between ACT and TAS, the model describes a similar relationship between shape and taper values and soil depth class. For a given shape, the change from shallow to deep occurs over a relatively narrow range of tapers (1.2 - 1.6 cm/m). Model predictions of depth class were correct at least 75 % of the time for both shallow and deep depth class predictions (Table 4.5).

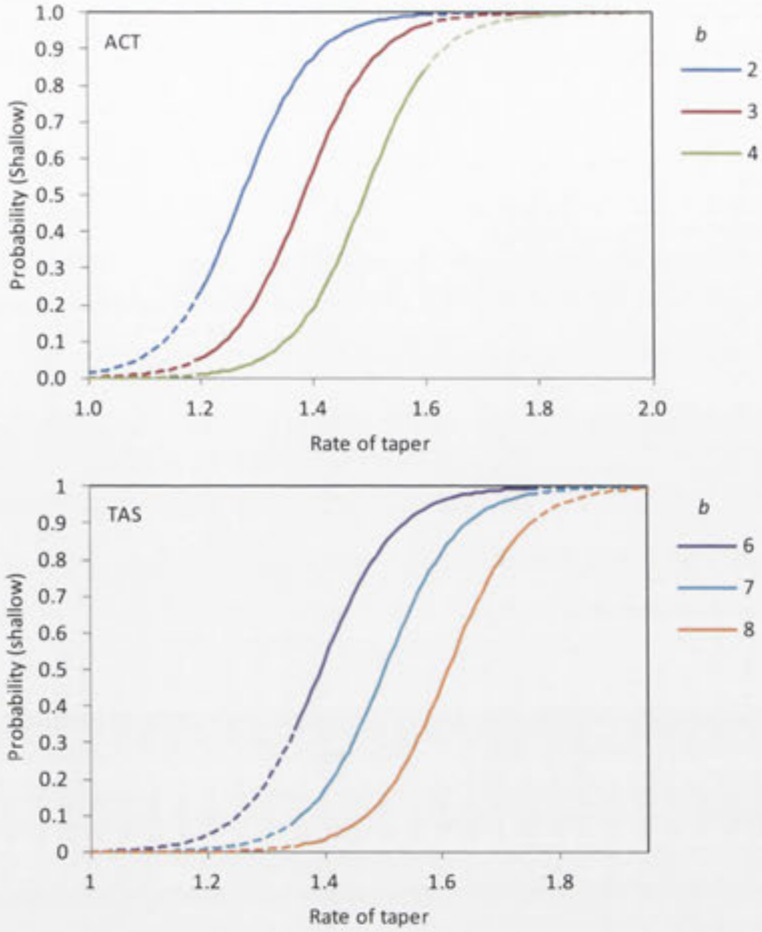


Figure 4.5 Prediction profile of logistic regression model for selected values of shape and taper for ACT and TAS case study sites. *Solid lines denote interpolated values and perforated lines denote extrapolated values.*

Table 4.5 The observed and predicted frequencies for the logistic regression of soil depth class on stem shape and taper with a cut-off of 0.50.

Observed	Predicted		% Correct
	Deep	Shallow	
Deep	12	5	70.59
Shallow	4	11	73.33
Overall % correct			71.88

The logistic regression of tree height with soil depth class indicated that individual tree height was a highly significant predictor of soil depth (Table 3.8). At both regions, deeper soils were associated with taller trees. Trees were approximately 10 m taller on average in TAS than ACT. As found for shape and taper, the relationship between height and soil depth was similar between the two regions. The model predicts that the change from shallow to deep soils occurs over a relatively narrow band of 4 m difference in tree height for both regions (Figure 4.6). Model predictions of soil depth class were correct approximately 71 % of the time (Table 4.6).

Table 4.6 Regression statistics for logistic regression of soil depth class on individual tree height for ACT and TAS case study sites.

Whole model test

Model	-Log Likelihood	DF	χ^2	$P > \chi^2$
Difference	9.42	2	18.85	<0.0001
Full	12.76			
Reduced	22.18			

Logit R^2	0.42
Observations	32

Parameter estimates

Coefficient	β	SE β	χ^2	$P > \chi^2$
Intercept	-27.5	10.06	7.47	0.006
Region [ACT]	8.48	3.11	7.42	0.006
Region [TAS]	-8.48 [a]	.	.	.
Height	1.43	0.52	7.44	0.006

Prediction formula:

$$Prob[Shallow] = \frac{1}{1 + e^{Ln[Deep]}}$$

where $Ln[Deep] = -27.50 + Region + 1.43 * Height$

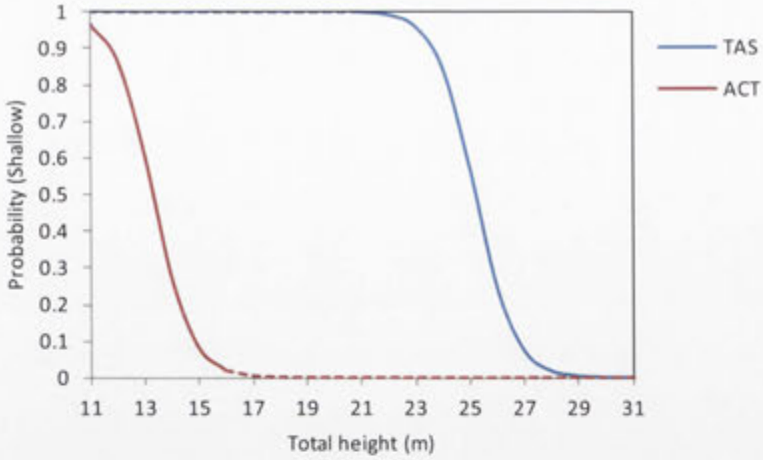


Figure 4.6 Prediction profile of logistic regression model for distribution of individual tree height at ACT and TAS case study sites. *Solid lines denote interpolated values and dotted lines denote extrapolated values.*

Table 4.7 The observed and predicted frequencies for the logistic regression of soil depth class on individual tree height with a cut-off of 0.50.

Observed	Predicted		% Correct
	Deep	Shallow	
Deep	11	4	73.33
Shallow	5	12	70.58
Overall % correct			71.88

4.4 Discussion

Neither shape nor taper were significant predictors of soil depth in a simple linear regression, but both parameters were statistically significant ($p < 0.05$) in a logistic regression. There appeared to be a consistent relationship between stem shape and taper in the butt swell and soil depth in the ACT sites and Tasmanian sites, despite differences in stand age, site and soil type. The model suggests that deeper soils are associated with decreasing tapers and higher values of stem shape at both sites.

As could be expected, individual tree height was significantly related to soil depth class. However, all statistically significant differences in height between shallow and deep soils were also very close to the precision levels of the hypsometers used for measurement. Standard deviations were almost 10 % of the measured value, which for a 20 m tall tree equates to an error of about 2 m. The expected precision for a standard hypsometer is said to be about 2.5 % of the total tree height; and modern hypsometers are now purported to be accurate to at least 1 % of total tree height (Brack and Wood 1996). In our own tests, the precision of Vertex hypsometers were found to vary by up to 4 % of total height (Appendix 1). Mean differences of up to 10 % have been reported in conifer forests (Coops, Wulder et al. 2004).

Conventional field inventory techniques of height measurement are also subject to object-based error. Accurate and precise measurements of tree height are generally difficult to obtain in densely stocked forest stands, particularly where crown closure has already occurred and the tops of trees are not easily visible (Anderson, Reutebuch and Schreuder 2010). In addition to this, one of the most frequent sources of error in height estimation is the failure to recognise and account for tree lean. Depending on the direction from which the tree is observed, obvious tree leans of more than 6 ° incur errors that may range between +11.1 % to -10 % of true height if not correctly accounted for. A tree with even a slight lean of 3°, which is difficult to detect by eye, will incur an error ranging from +5.4 % to -5.2 % if it were measured as though vertical (Wood, Turner and Brack 1999).

Tree height may be strongly related to soil depth, but its utility may be reduced by the difficulty of height estimation using conventional ground-based techniques. In recent years airborne techniques such as airborne laser scanning instruments (lidar) have received significant attention by the Australian softwood plantation sector. However, unless the intensity of lidar returns is very high, estimation of individual tree height is typically imprecise and underestimated. When compared with Vertex measured trees, Stone, Turner et al. (2009) reported a negative bias of up to 2 m in lidar derived mean tree height; and note that the bias is particularly obvious in smaller trees which are less likely to score a direct hit by the lidar beam on the tree top.

Error in tree height affects model predictions of depth directly in the tree height model and indirectly in the stem shape and taper model through the estimation of stem shape and taper. The sensitivity of model predictions of depth class to a 2 m difference in tree height (approximately 10 % error for a 20 m tall tree) was compared between the tree height model and the stem shape and taper model using an arbitrary selection of 12 trees from the ACT and TAS study sites (Appendix 5). It was found that the shape and taper model predicted a slightly greater number of correct depth class predictions overall compared with the tree height model; however, the difference was not marked enough to be significant.

4.5 Summary and conclusions

The findings of this preliminary work support the hypothesis that stem shape and taper are significantly related to changes in soil depth class. Despite obvious differences in site and stand characteristics, a general relationship was identified in both the shallower soils of the ACT sites and the relatively deeper soils of the Tasmanian site. For expediency, soil depth class was used as a crude proxy for soil depth and a relatively small sample of individual trees were measured. The promising results of this work provided justification for more work to generate more data with more detailed soil assessment. The next stage of this investigation is discussed in the following chapter.

Chapter 5: Developing the soil depth model in South Australia

5.1 Introduction

Plantations of *P. radiata* have been grown for over a century in the Mount Gambier plantation region on sites that differ markedly in site productivity, depending on the nature and depth of the soil profile (Lewis, Keeves and Leech 1976). The availability of compartment-level maps of soil type for the region presented an opportunity to employ a more purposive method of sampling to enhance variation in the soil depth data obtained and thus improve modelling. As work in the previous chapter was based on a small dataset and visual assessment of change in soil depth, the overall objective of this case study was to investigate the relationship between stem shape, taper and soil depth in greater detail by incorporating substantially more data and the measurement of soil depth. The specific aims of this case study were to:

1) Improve the stem shape-taper model for predicting soil depth class developed in the previous chapter by incorporating more data from a third region.

2) Investigate the development of a quantitative model for predicting absolute soil depth, using stem shape and taper.

3) Develop the above models using individual tree height and compare these with the stem shape and taper models.

5.2 Methods

5.2.1 Location and description of the sample site

Sampling was conducted in the Mount Burr Forest District (37°33′S, 140°28′E) near Mount Gambier in south-east South Australia (Figure 5.1). Rainfall in the region is relatively high with minimum average annual rainfall over the reserve estimated to be in the range of 787 to 820 mm, maximum temperature of 19.2 °C and minimum temperature of 8.8 °C.

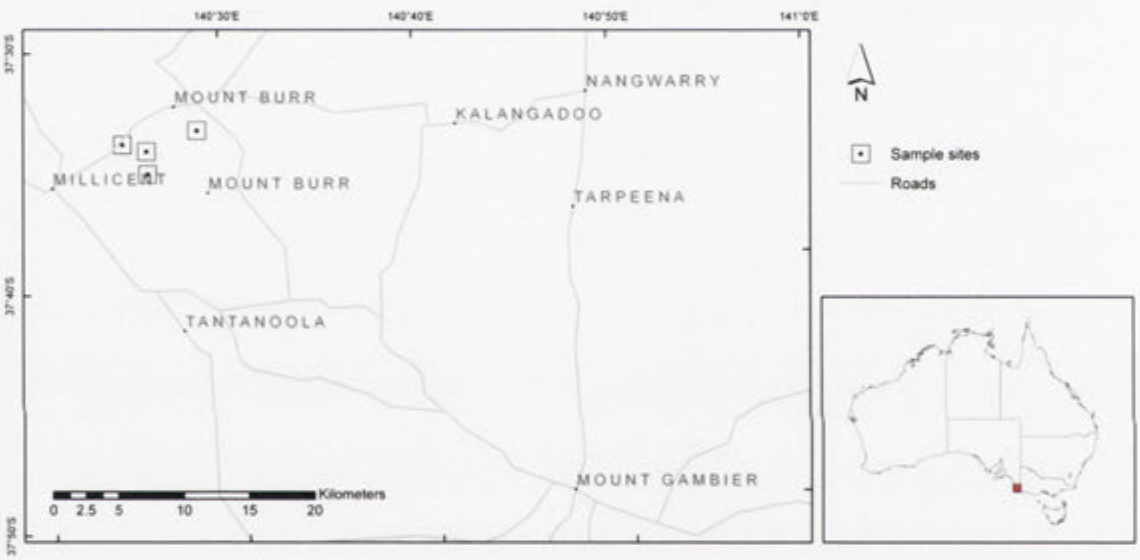


Figure 5.1 Location of sample sites in Mount Burr plantation, Mount Gambier.

The plantation previously supported two crops of *P. radiata* planted in 1924 and 1959. Calcarenite dune remnants occupy extensive areas. The landscape is volcanic and soils are predominantly sandy soils of Aeolian origin, often highly leached, with terra rossa and basaltic loams occurring where parent materials are near to the surface. Topography is relatively flat, with an altitudinal range of 80-150 m (Gepp, Boardman et al. 2007). The surface (A) horizon of coarse well-drained organic matter, approximately 20 cm in depth, overlie a weakly developed B1 horizon consisting of 2-3 m brownish-yellow Rudosols and Tenosols and a B2 horizon of sandy clay, which varies from 3-5 m in depth. Detailed soil physical and chemical descriptions of the site are given in Nambiar and Bowen (1986). The site is characterised by a relatively shallow water retentive layer. This is usually an illuvial or unrelated clay, or sandy clay horizon, but in some soils, soft or hard pans of compacted or cemented organic sand and gravels are continuous enough to prevent further downward movement of water over substantial areas (Lewis, Keeves and Leech 1976). The soil is considered to be low in fertility compared to other plantation sites in the region, and is primarily nitrogen and phosphorus limited. Stands were aged 17 and 18 years at the time of measurement, were unpruned and had been thinned.

Sample plots were located in five neighbouring plantation compartments of similar age classes. These were selected on the basis of age class as well as variability in soil type, as described in Section 3.4.1. Plots were positioned along transects ranging in length from 0.5 km to 1 km, at regular intervals of either 50 m or 100 m. The length of transects and the number of plots measured depended on the size of the compartment. Compartments ranged in size from about 20 to 50 ha.

Each plot comprised of 6 trees. Soil samples were taken at a single point in the centre of each plot using an auger. Soil type was assessed using the South Australian soil classification system (Lewis, Keeves and Leech 1976) and soil depths were measured down to the water retentive layer or to a maximum depth of 2.7 m. At each plot, tree heights and diameters over bark were measured and stem shape and taper in the bottom 2 m of the tree were calculated (Table 5.1).

Table 5.1 Mean stem shape and taper in the basal 2 m of the stem, tree height and other sample characteristics at SA, ACT and TAS case study sites. *Bracketed values denote the standard deviation.*

	SA	ACT	TAS
Age (years)	18, 19	14, 15	29
Thinning	Thinned	Unthinned	Thinned
Plot size (individual trees)	6	2-4	2
Sample size (plots)	34	10	4
Mean DBH (cm)	24.7 (3.4)	23.4 (3.4)	32.7 (4.5)
Mean height (m)	23.5 (2.2)	13.3 (1.4)	25.5 (2.8)
Mean stem shape	6.86 (0.57)	2.59 (0.82)	6.71 (0.87)
Mean taper	1.49 (0.57)	1.35 (0.08)	1.47 (0.12)

* at time of measurement

5.2.2 Data exploration

The distributions of shape, taper and tree height were examined using box-plots and histogram, as described in Chapter 3 (Section 3.5). A two-sided independent sample t-test was used to test for significant ($p < 0.05$) relationships between tree attribute parameters and both soil depth class and absolute soil depth. In this study, shallow soils were defined as depths less than 1.0 m and deep soils were defined as depths greater than or equal to 1.0 m. For consistency with the methods described in the previous chapter, the depth measurements collected here were also assigned to depth classes. The selection of a threshold depth of 1.0 m was mostly an arbitrary choice, but considering the small sample size, it was desirable to choose a threshold that would enable an almost equal division of plots into shallow and deep classes. Sensitivity analysis around this depth (from 0.4 - 1.5 m) indicated that results were not sensitive to the choice of threshold depth.

5.2.3 Development of models

In this study, models were developed for depth class, as in the preceding study (Chapter 4), and for absolute soil depth. For both models, parameters were selected by fitting the full factorial model (up to third order interactions) and removing least significant, highest order interactions preferentially until a reduced model with all significant ($p < 0.05$) parameters was obtained.

5.2.3.1 Depth class model

A logistic regression model was fitted using the combination of the three datasets from ACT, TAS and SA. As each plot of trees had been associated with a single soil measurement in the SA site, the estimated shape and taper values for each individual tree were averaged to generate plot means. Use of the earlier ACT and TAS datasets necessitated the conversion of individual tree measurements to plot means. For these sites, the number of trees allocated to each plot ranged from 2 - 6 trees for each depth class. Independent variables tested were tree height, shape (b), taper (k) and region.

5.2.3.2 Absolute depth model

An absolute depth model was developed using the limited set of soil depth measurements collected from the South Australian study site using regression analysis described in Chapter 3, Section 3.5. As above, independent variables tested were tree height, shape (b), taper (k) and region.

5.3 Results

5.3.1 Data exploration

The shape, taper and height of trees at the South Australian site were more similar to trees at the Tasmanian site, than the ACT site. The average shape of trees at the South Australian site was 6.7, with a mean taper of about 1.5 cm/m and mean height of 23.5 m. As found for previous study sites, there was no significant difference in either shape or taper with change in soil depth class in the South Australian site, but trees were significantly ($p < 0.05$) taller in deeper soils than shallower soils (Figure 5.2).

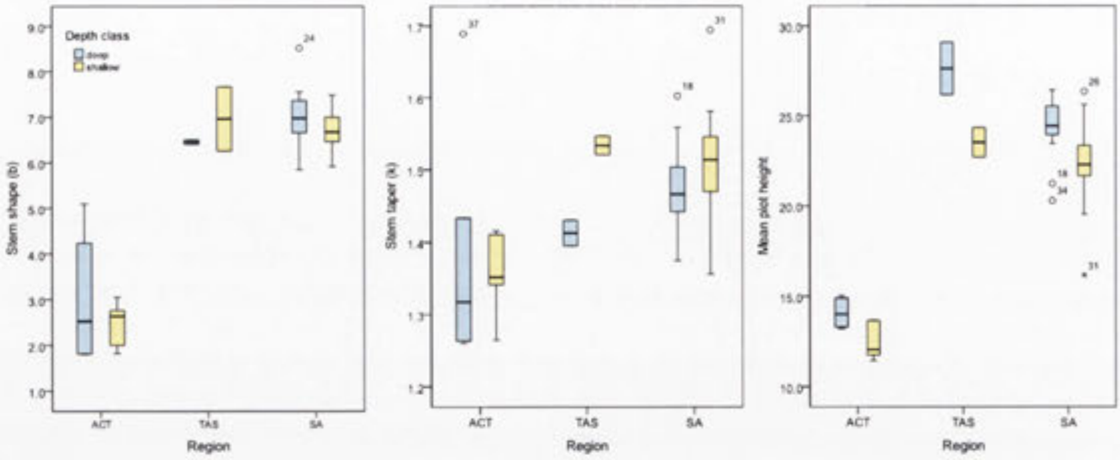


Figure 5.2 Boxplots of stem shape, taper and height grouped by depth class for SA, ACT and TAS case study sites.

The maximum recorded height of trees was about 26 m for both deep and shallow depth classes, but the minimum height of trees in shallow soils was about 4 m less than the minimum height of trees in deep soil classes. For the Tasmanian site, the bulking up of individual tree measurements to plot means reduced sample size to the extent that the difference in individual tree heights originally observed were no longer significant (Table 5.2). However, this resulted in the non-significant difference in taper between deep and shallow sites originally observed in the Tasmanian site becoming significant ($p < 0.05$).

Table 5.2 Differences in stem shape (*b*), taper (*k*) and height with change in soil depth class for ACT, TAS and SA case study sites.

Region	Parameter	Depth class	n	Mean (SE)	*p*-value*	Mean difference	95 % Confidence Interval
ACT	*b*	Deep	5	3.10 (0.66)	0.39	0.64	[-0.99, 2.27]
		Shallow	5	2.45 (0.23)			
	k	Deep	5	1.39 (0.08)	0.68	0.04	[-0.16, 0.23]
		Shallow	5	1.36 (0.02)			
	Height	Deep	5	14.09 (0.38)	0.03	1.58	[0.16, 3.00]
		Shallow	5	12.52 (0.48)			
TAS	*b*	Deep	2	6.45 (0.05)	0.54	-0.51	[-3.54, 2.52]
		Shallow	2	6.96 (0.70)			
	k	Deep	2	1.41 (0.02)	0.03	-0.12	[-0.22, -0.03]
		Shallow	2	1.53 (0.01)			
	Height	Deep	2	27.62 (1.45)	0.13	4.1	[-3.07, 11.28]
		Shallow	2	23.51 (0.82)			
SA	*b*	Deep	19	6.99 (0.14)	0.15	0.29	[-0.11, 0.68]
		Shallow	15	6.70 (0.12)			
	k	Deep	19	1.48 (0.01)	0.14	-0.03	[-0.08, 0.01]
		Shallow	15	1.51 (0.02)			
	Height	Deep	19	24.36 (0.36)	0.005	-2.05	[-0.66, -3.43]
		Shallow	15	22.31 (0.62)			

**p*-value based on a 2-sided independent sample t-test

5.3.2 Depth class model

Parameters in the final form of the logistic model were shape, taper and region. In contrast to the preliminary model, the region parameter was significant in this development of the regression model (Table 5.3). The inclusion of data from additional regions produced a slight decrease in model accuracy.

Table 5.3 Regression statistics for the logistic regression of soil depth class on stem shape (*b*) and taper (*k*) for ACT, TAS and SA case study sites.

Whole model test

Model	-Log Likelihood	DF	χ^2	$P > \chi^2$
Difference	5.18	4	10.37	0.04
Full	27.92			
Reduced	33.1			

Logit R^2	0.16
Observations	48

Parameter estimates

Coefficient	β	SE β	χ^2	$P > \chi^2$
Intercept	12.95	6.76	3.67	0.05
Region [ACT]	4.21	1.95	4.67	0.03
Region [SA]	-1.96	1.05	3.52	0.06
Region [TAS]	-2.25	.	.	.
b	2.03	0.81	6.34	0.01
k	-16.56	6.69	6.12	0.01

Prediction formula:

$$Prob[Shallow] = \frac{1}{1 + e^{Ln[Deep]}}$$

where $Ln[Deep] = 12.95 + Region + 2.03 * b - 16.56 * k$

Consistent with the preliminary model, this model also indicates that deeper soils are associated with decreasing tapers and higher stem shape parameters for all three regions (Figure 5.3). For a given shape, the transition from shallow to deep soils occurs over a relative narrow range of tapers. For example, a transition occurred over a range of 1.0 to 1.5 for a shape value of 5 at both TAS and SA sites. Although the range of taper values was the same at the ACT site as for the TAS and SA sites, minimum and maximum values were slightly higher at 1.4 - 1.9 cm/m. Model predictions of depth class were correct in about 67 % of cases for both shallow and deep soils (Table 5.4).

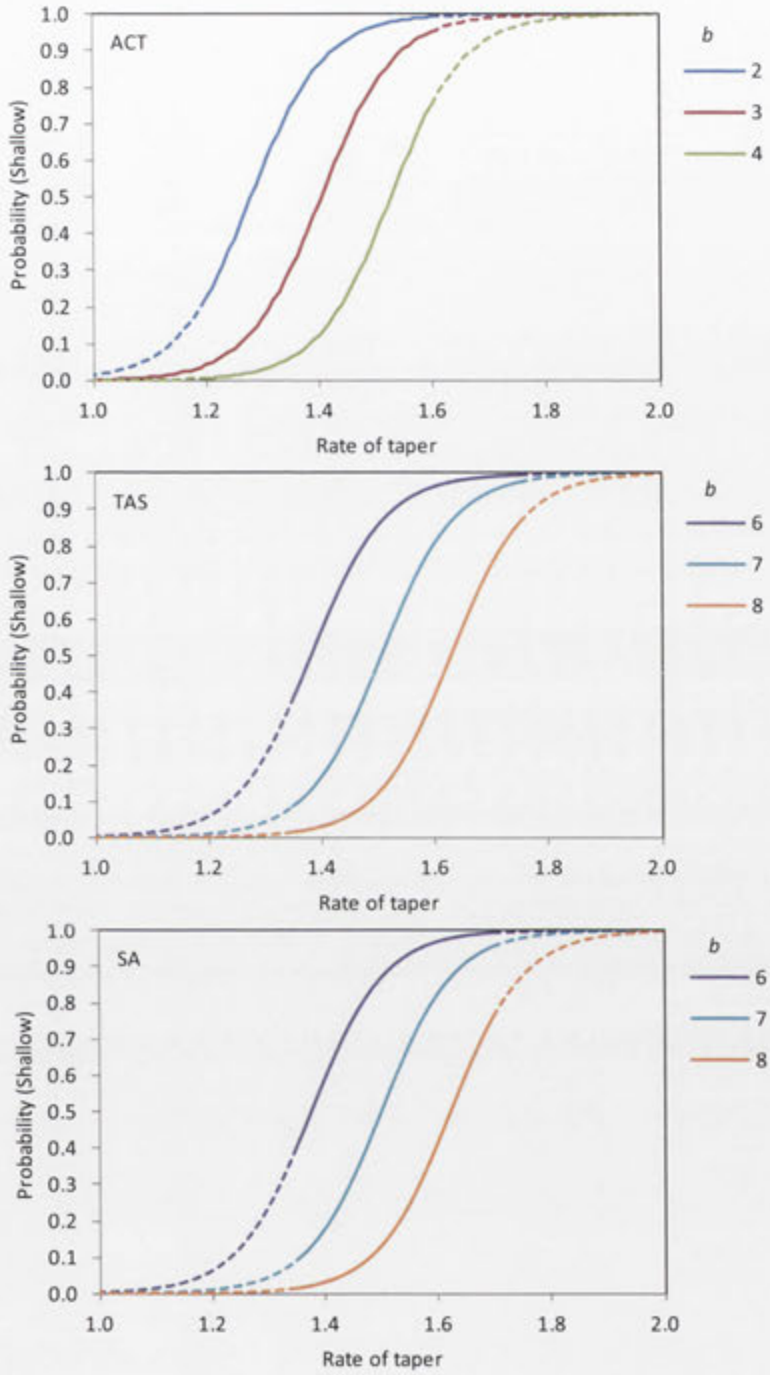


Figure 5.3 Prediction profiles for the logistic regression of soil depth class on stem shape and taper for ACT, TAS and SA case study regions. *Solid lines denote interpolated values and perforated lines denote extrapolated values.*

Table 5.4 The observed and predicted frequencies for the logistic regression of soil depth class on stem shape and taper for ACT, TAS and SA case study sites, with a cut-off of 0.50.

Observed	Predicted		% Correct
	Deep	Shallow	
Deep	20	10	66.67
Shallow	6	12	66.67
Overall % correct			66.67

Individual tree height was a highly significant predictor of depth class (Table 5.5). Deeper soils were associated with taller trees at all case study sites (Figure 5.4). Based on the sharpness of the transition from shallow to deep classes, the depth class model fitted with individual tree height performed better than the model fitted using stem shape and taper (Table 5.6).

Table 5.5 Regression statistics for the logistic regression of soil depth class on individual tree height for ACT, TAS and SA case study sites.

Whole model test

Model	**-Log Likelihood**	**DF**	χ^2	$P > \chi^2$
Difference	6.37	3	12.74	0.01
Full	20.65			
Reduced	27.02			

Logit R^2	0.24
Observations	39

Parameter estimates

Coefficient	**β**	**SE β**	χ^2	$P > \chi^2$
Constant	-14.53	5.08	8.17	0.004
Region [ACT]	5.24	1.92	7.42	0.006
Region [SA]	-2.02	0.93	4.69	0.03
Region [TAS]	-3.22	.	.	.
Height	0.7	0.24	8.22	0.004

Prediction formula:

$$Prob[Shallow] = \frac{1}{1 + e^{Ln[Deep]}}$$

where $Ln[Deep] = -14.53 + Region + 0.7 * Height$

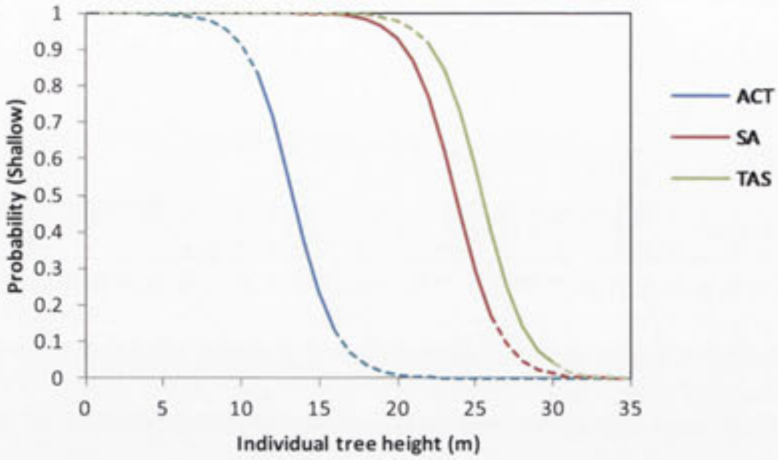


Figure 5.4 Prediction profiles for the logistic regression of soil depth class on individual tree height for ACT, TAS and SA case study regions. *Solid lines denote interpolated values and perforated lines denote extrapolated values.*

Table 5.6 The observed and predicted frequencies for the logistic regression of soil depth class on individual tree height for ACT, TAS and SA case study sites, with a cut-off of 0.50.

Observed	Predicted		% Correct
	Deep	Shallow	
Deep	15	4	78.95
Shallow	5	15	75
Overall % correct			76.92

5.3.3 *Absolute depth model*

Shape and taper together in a multiple regression were significant predictors of absolute soil depth. Parameters in the final model were shape (b), taper (k) and their interaction ($b*k$) (Table 5.7). In the regression, shape and taper explained about 43 % of the variation in depth in the South Australian site with an acceptable error distribution. A model fitted with tree height (mean plot height) alone explained 32 % of variation in soil depth (Table 5.8). However, the distribution of residuals for the height model showed signs of non-normality and heteroskedacity.

Table 5.7 Regression statistics for multiple regression of absolute soil depth on stem shape (b) and taper (k) for SA case study site.

Summary of fit

R^2	0.43
RMSE	0.53
Observations	28

Analysis of variance

Source of variation	DF	SS	MS	F-ratio	Prob > F
Model	3	5.14	1.71	6.1	0.003
Error	24	6.74	0.28		
Total	27	11.88			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob > |t|
Intercept	4.73	2.5	1.9	0.07
b	0.83	0.21	4.05	< 0.001
k	-6.12	1.94	-3.15	0.004
$(b - 6.84)*(k - 1.50)$	-5.72	2.81	-2.04	0.05

Prediction formula:

$$Depth = 4.73 + 0.83 * b - 6.12 * k - 5.72 * (b - 6.84) * (k - 1.50)$$

Table 5.8 Regression statistics for multiple regression of absolute soil depth on individual tree height for SA case study site.

Summary of fit

R^2	0.33
RMSE	0.54
Observations	20

Analysis of variance

Source of variation	DF	SS	MS	F-ratio	Prob > F
Model	1	2.66	2.66	8.98	0.008
Error	18	5.33	0.3		
Total	19	7.99			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob > |t|
Intercept	-2.2	1.1	-2	0.06
Height	0.14	0.05	3	0.008

Prediction formula:

$$Depth = -2.20 + 0.14 * Height$$

The regression model suggests that there is a linear relationship between shape and taper in the butt swell section and soil depth in the South Australian site (Figure 5.5). As could be expected, the absolute depth model predicts increasingly deeper soils with decreasing tapers and higher stem shape parameters. A linear relationship between individual tree height and soil depth was also found (Figure 5.6). However, the poor distribution of residuals for the height model suggests that its apparent precision may be biased.

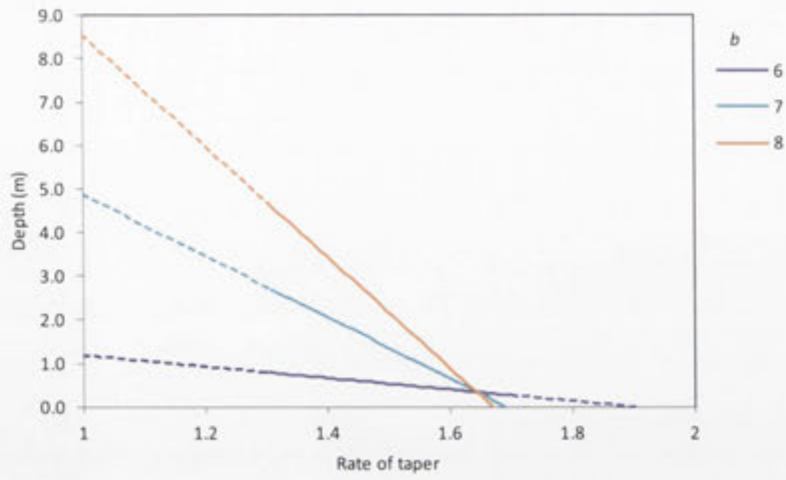


Figure 5.5 Predicted soil depth for the multiple regression of absolute soil depth on stem shape (b) and taper (k) for the SA case study site. *Solid lines denote interpolated values and perforated lines denote extrapolated values.*

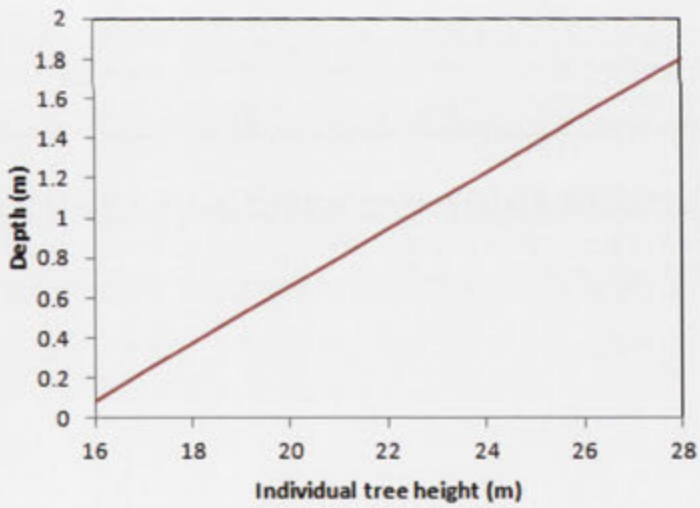


Figure 5.6 Predicted soil depth for the multiple regression of absolute soil depth on individual tree height for the SA case study site.

5.4 Discussion

The relationship between stem shape and taper in the butt swell section of the stem and soil depth identified in earlier work was confirmed by the findings of this stage of work. Consistent with the preliminary model developed in the previous chapter, parameters in the final model were shape, taper and region. Deeper soils were associated with lower tapers and higher values of stem shape in all three regions, but as found for the preliminary model, shape, taper and predicted depth differed between regions. The region parameter was not significant in the preliminary model given the limited sample size, but appeared to account for broad differences in climate and genotypes between regions. The addition of new data from South Australia resulted in region becoming a significant parameter in the final model. This confirmed the need for a regional parameter to reduce the residual error associated with variations between regions.

The quantitative prediction of absolute soil depth using stem shape and taper in the butt swell was explored during this stage of work. The final regression model describes a linear relationship between stem shape, taper and soil depth, with soil depth increasing with decreasing tapers and higher stem shape parameters at all sites. It was observed that the plotted graphs for each shape converged at a depth of about 0.5 m, which implied that a linear relationship may not be valid in very shallow soils of less than 0.5 m and that the model at this point in the soil profile has probably been extrapolated beyond its useful range.

The findings of this stage of work demonstrate that stem shape and taper may be more powerful predictors of absolute soil depth than tree height. The poor distribution of errors for the height model indicates that there are additional factors, such as co-related variables, that have not been included in the model. The error distribution of the height model suggests that other factors may influence the height response of the tree to changes in soil depth.

5.5 Summary and conclusions

The relationship between stem shape, taper and depth class originally identified in the preceding chapter was confirmed in this stage of work. As in the preliminary model, parameters in the final model were stem shape, taper and region. A larger dataset resulted in the region parameter becoming significant ($p < 0.05$). This suggests that the model requires calibration for the region to which it is applied to reduce the residual error associated with differences in factors that vary across regions, such as climate.

The absolute soil depth model describes a linear relationship between stem shape, taper and soil depth at the South Australian site. The model suggests that soil depth increases with decreasing taper and higher values of stem shape, which is consistent with that described by depth class models. As the model was developed using a relatively limited dataset for a single region, more data is required to improve the model. This work is described in the following chapter.

Chapter 6: Improving the soil depth model and investigating relationships with other soil properties

6.1 Introduction

The soil is multidimensional and many other soil factors in addition to soil depth interact to determine tree growth. Results thus far indicate that even though there are regionally specific differences in the relationship between soil depth and the butt swell, deeper soils are consistently associated with higher stem shapes and lower rates of taper. As soil depth acts as a surrogate for more complex soil variables, it is hypothesised that it may also be possible to quantify these other relationships. Soil factors that define soil effective volume and other favourable conditions for growth include water holding capacity, coarse fragments, bulk density, and nutrients (nitrogen and phosphorus). In this stage of work, a selection of these soil physical and chemical properties were analysed as part of an exploratory study to determine if any individual or combination of these variables, were more strongly related to stem shape and taper in the butt swell than soil depth alone.

This stage of work had two aims and the chapter is divided into two parts on this basis. The main objective of this stage of work was to further improve the soil depth model developed in preceding chapters by the addition of data from New South Wales. The secondary aim of this work is to analyse a broader range of soil variables to explore relationships with stem shape and taper in the butt swell.

6.2 Methods

6.2.1 Location and description of sample sites

Sampling was conducted in two neighbouring *P. radiata* plantation areas, Green Hills State Forest (35.52°S, 148.05°E) and Carabost State Forest (35.65°S, 147.80°E), located about 30 km south of Tumut, New South Wales (Figure 6.1). Sample sites in Green Hills were all second rotation plantings on ex-native forest. Sample sites in Carabost were all first rotation plantings on cleared, mostly unimproved pasture.

Figure 6.1 Location of Green Hills and Carabost case study sites.

The Green Hills and Carabost sites are characterised by contrasting site and soil conditions. The Green Hills site is located at a higher altitude and experiences higher rainfall than the Carabost site (Table 6.1). The geology in Green Hills is saprolite and granodiorite. Soils are Rudosols and Tenosols on crests, red Chromosols and Kandosols soils on upper slopes, brown Chromosols and Kandosols on lower slopes and yellow Chromosols and Kandosols in drainage lines. Soils were generally deep (> 3 m) on upper slopes and very deep (> 6 m) on mid to lower slopes/drainage lines. The presence of the saprolite layer made distinguishing any root-impeding layer difficult. Carabost forest is situated on Ordovician sediments, consisting of shales, slates, mudstones and siltstones. Soils are Rudosols and Tenosols derived from Ordovician shales. Soils are relatively shallow, ranging from 0.4 m on upper slopes to about 2 m on lower slopes.

Table 6.1 Key biophysical characteristics of Green Hills and Carabost sites.

	Green Hills	Carabost
Mean annual rainfall (mm)	1221.3	934
Mean max. temperature (°C)	6	6.2
Mean min. temperature (°C)	17	20
Elevation (m)	785	420

Source: BoM weather stations (Green Hills State Forest, Carabost State Forest)

6.2.2 Measurement of soil and trees

Field sampling At both sites, the selected compartments were stratified by slope position (ridge top, mid-slope, valley bottom) and sample plots were randomly positioned within strata at least 50 m apart. Soils in Green Hills were generally very deep (> 6 m). Due to a lack of shallow soils in Green Hills, several sample plots (10 plots) were located on a rocky granite outcrop, where trees were visibly shorter. The rocky layer was non-contiguous, as assessment of soil depth showed that soils were at least 2 m deep at selected points. As tree spacings were irregular at this site, the number of trees in each sample plot was reduced to four trees to ensure that in as many cases as possible, selected trees were representative and located away from any gaps in the planting row. Stands at both sites were aged 14 years at the time of measurement. Stem shape, taper and total tree height were measured using the general methods described in Chapter 3.

Two methods were used to collect soil samples. At both sites, a 5 tonne excavator was used to excavate soil pits, approximately 2 m long by 0.5 m wide, in the centre of each sample plot (Figure 6.2). The maximum depth of assessment was 3 m. In Green Hills, soils were typically gradational and soil boundaries were difficult to distinguish. Hence, soil samples were collected at approximately 0.5 m intervals from the base of the pit to the A horizon. In Carabost, where soil horizons could be clearly distinguished, soil samples were collected from each horizon. Depths of the A, B and/or C horizons were measured. Effective soil depth was measured if root-impeding layers were present at depths less than 2.5 m; otherwise, the maximum depth of the soil pit was measured.

Figure 6.2 Excavation of soil pits at Green Hills and Carabost sites.

Soil chemical analyses Soil samples were prepared for analysis by air-drying and sieving through a 2 mm sieve to separate rock from fine material. Percentage rock was calculated and the under 2 mm fraction was analysed for total and plant-available phosphorus (P), total and plant-available nitrogen (N), plant-available water holding capacity (AWC), total organic carbon (% TOC), pH and electrical conductivity (EC). Standard laboratory methods were used for all soil chemical analyses and are described in Appendix 2.

Total N and P were determined by acid digestion using methods adapted from Rayment and Lyons (2011) (A2-1). Available N (nitrate) was determined using methods adapted from Rayment and Lyons (2011), with non-automated colour measurement using the Hach spectrophotometer cadmium reduction method (Hach Company 1996-2000) (A 2-2). Available (labile) P was determined by resin extraction using methods adapted from Robertson, Coleman et al. (1999) (A 2-3). Total carbon and total nitrogen were determined using the LECO CNS2000 Analyser at Southern Cross Geosciences Laboratories. Soil pH and EC were determined for a 1:5 soil/water extract using a digital pH/Conductivity multi-meter (A 2-4). Available water holding capacity was estimated from texture class, sand size fraction and percentage stoniness using methods described in Hazelton and Murphy (2007). Texture classes were determined by field (hand) texture methods on the < 2 mm fraction. Sand size fraction was visually assessed for the 2 mm fraction and percentage stoniness was visually assessed for the total sample.

6.2.3 Data exploration

The distributions of shape, taper and tree height were examined using box-plots and histograms as described in Chapter 3 (Section 3.5.1). An independent sample two-sided t-test was used to test for significant ($p < 0.05$) relationships between tree parameters (shape, taper and height) and both soil depth class and absolute soil depth. The distributions of soil attribute variables, grouped by soil horizon, were assessed using box-plots, histograms and descriptive statistics. Soil attribute variables examined were depth of soil horizons and total depths, available and total phosphorus, available and total nitrogen, total organic carbon, available water holding capacity, pH, and electrical conductivity.

6.2.4 Development of models

6.2.4.1 Improving soil depth models by incorporating NSW data

Depth class model The depth class model based on three regions (ACT, TAS, SA), developed and reported in preceding chapters, was further optimised by incorporation of data from Green Hills and Carabost study sites, which were combined and classed as a single region (NSW). For this region, plots with soil depths greater than 1 m were defined as 'deep' and plots with soil depths less than 1 m were defined as 'shallow'. There were a sufficient number of deep and shallow sites in Carabost, but by this definition, almost all sites in Green Hills were classified as 'deep' soils. Due to the lack of shallow depth classes, trees growing on a rocky outcrop were sampled. Soils at this site were classified as 'shallow', although soil depth was found to be greater than 2.5 m at several points across the site, indicating that the rocky layer was non-contiguous. Overall soil volume would nevertheless be limited due to the presence of the rocky outcrop.

Model parameters were selected by fitting the full factorial model (up to third order interactions) and removing least significant highest order interactions preferentially until a reduced model in which all parameters were significant ($p < 0.05$) was obtained.

Absolute soil depth model The preliminary absolute depth model developed using the South Australian dataset in the preceding chapter, was improved by the addition of more data and a second region. Soil depth measurements from New South Wales were combined with the South Australian dataset and the model refitted. As all soils were deep in Green Hills, it should be noted that soil depth observations refer mostly to the maximum depth of the soil pit, rather than depth to an impervious layer. As the Green Hills data comprised a substantial portion of the overall NSW dataset, the data was still included in modelling, but any subsequent interpretation of results must take this into account.

Model evaluation Models were evaluated using a method of cross-validation in which the model is derived from n - 1 observations and used to predict soil depth for the one observation not used in model construction. This was repeated for all single data point omissions to obtain an unbiased estimate of model error. Results of the cross-validation are presented as contingency tables for logistic regression models and by plotting residuals and reporting RMSE values for multiple regression models.

6.2.4.2 Examining the two-way relationship between stem shape and taper in the butt swell and soil properties

Using stem shape and taper in the butt swell to predict soil properties

Possible relationships between individual tree attribute variables (shape, taper and height) and soil attribute variables in the A and B horizons for both study sites were explored using a matrix of pair-wise scatterplots. The direction and strength of correlations as described by the correlation coefficient (r) were noted. Pair-wise relationships with an r-value above a critical level ($p < 0.05$) were identified. As correlation coefficients (r) and p-values are related via sample size, critical values of r were selected based on sample size (Forestry and Timber Bureau 1975). For $\alpha = 0.05$, these are $r = 0.35$ (n = 30) at Green Hills and $r = 0.43$ (n = 19) at Carabost. Any statistically significant relationships identified were tested in a simple linear regression.

Although C horizon soil variables were also sampled in soil profiles where a C horizon was present, nutrient levels were low and in many cases, below the detection limit or sensitivity of analytical methods used. For this reason and as C horizons often extended below the rooting depth of the trees, C horizon samples were excluded from further analysis.

Using soil properties to predict stem shape and taper in the butt swell The relationship between stem shape and taper and combinations of soil parameters were examined in a multiple regression. Soil variables tested were those that had been identified in previous explorations (described above) as having a relatively strong correlation ($r > 0.5$) with either stem shape or taper. Soil variables were analysed by soil horizon. As the sample size was limited, no more than six soil variables were introduced into the model at any one time to avoid overparameterisation. A combination of forward and backward selection was used to select a model with all significant ($p < 0.05$) parameters.

6.3 Results

6.3.1 Data exploration

The shape and taper in the basal 2 m of trees at the Green Hills and Carabost sites were more similar to the South Australian and Tasmanian study sites than the ACT study site. Values of stem shape were greater than 4.5 and taper values were approximately 1.5 cm/m at both NSW sites (Table 6.2). Sample sites were of the same age class but trees were taller by at least 1.0 m in Green Hills than in Carabost.

Table 6.2 Mean stem shape and taper in the basal 2 m of the stem, tree height and other sample characteristics across all south-eastern Australian case study sites. *Bracketed values denote the standard deviation.*

	NSW		SA	ACT	TAS
	Green Hills	**Carabost**			
Age* (years)	15	15	18, 19	14, 15	29
Thinning	Unthinned	Unthinned	Thinned	Unthinned	Thinned
Plot size (individual trees)	6	6	6	2 – 4	6
Sample size (plots)	30	22	34	4	2
Mean DBH (cm)	20.4 (3.6)	21.6 (2.9)	24.7 (3.4)	23.4 (3.4)	32.7 (4.5)
Mean height (m)	17.9 (1.7)	16.9 (1.7)	23.5 (2.2)	13.3 (1.4)	25.5 (2.8)
Mean stem shape	4.99 (0.52)	4.70 (0.58)	6.86 (0.57)	2.59 (0.82)	6.71 (0.87)
Mean taper	1.48 (0.047)	1.48 (0.052)	1.49 (0.067)	1.35 (0.083)	1.47 (0.12)

* at time of measurement

The distributions of stem shape, taper and height were normally distributed around their means, apart from stem shape in shallow soils for Carabost which was slightly skewed (Figure 6.3). As found for all other study sites, there was no significant ($p > 0.05$) difference in shape or taper with change in soil depth class for Carabost (Table 6.3). In Green Hills however, shape was significantly ($p < 0.05$) higher in deep soils than in shallow soils, but there was no significant difference in taper between depth classes. At both sites, trees were significantly ($p < 0.05$) taller in deep soils than in shallow soils. The tallest trees in Carabost were at least 1 m shorter than the tallest trees in Green Hills. Similarly, the shortest trees in Carabost were at least 2 m shorter than the shortest trees in Green Hills.

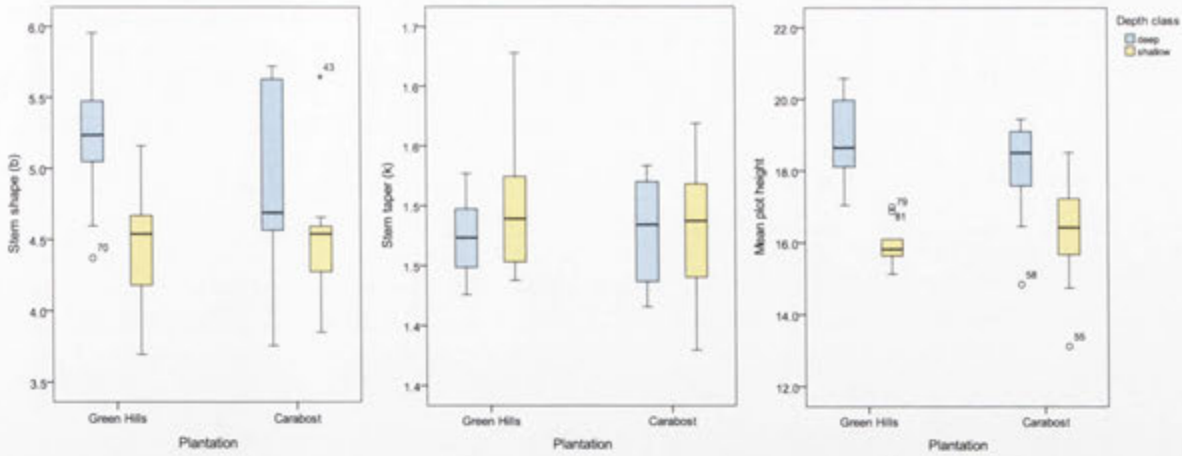


Figure 6.3 Boxplots of stem shape, taper and height grouped by soil depth class for Green Hills and Carabost case study sites.

Table 6.3 Differences in stem shape (*b*), taper (*k*) and height with change in soil depth class for Green Hills and Carabost case study sites.

Plantation	Parameter	Depth class	n	Mean (SE)	p-value*	Mean difference	95 % Confidence Interval
Green Hills	*b*	Deep	20	5.22 (0.08)	< 0.001	0.71	[0.40, 1.03]
		Shallow	10	4.50 (0.14)			
	k	Deep	20	1.47 (0.01)	0.07	-0.03	[-0.07, 0.002]
		Shallow	10	1.51 (0.02)			
	Height	Deep	20	18.90 (0.24)	< 0.001	2.94	[2.20, 3.67]
		Shallow	10	15.96 (0.18)			
Carabost	*b*	Deep	9	4.96 (0.23)	0.11	0.46	[-0.12, 1.03]
		Shallow	10	4.51 (0.15)			
	k	Deep	9	1.48 (0.02)	0.97	0.001	[-0.05, 0.05]
		Shallow	10	1.48 (0.02)			
	Height	Deep	9	17.99 (0.50)	0.02	1.76	[0.30, 3.23]
		Shallow	10	16.22 (0.48)			

**p*-value based on a 2-sided independent sample t-test

Examination of the distributions of values for each soil attribute showed that some attributes were more variable than others and would potentially be more useful in a regression (Figure 6.4). Available nitrogen in Green Hills, for instance, showed relatively high variation, while available phosphorus and total nitrogen showed minimal variation.

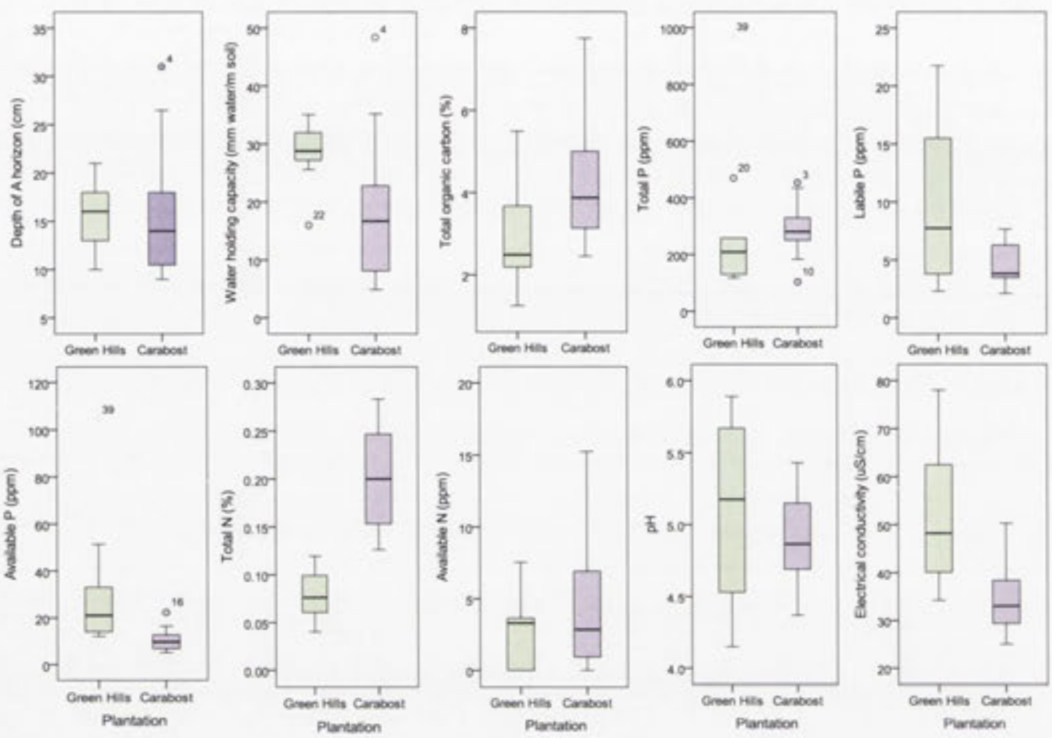


Figure 6.4 Boxplots of A horizon soil properties for Green Hills and Carabost case study sites.

6.3.2 Development of models

6.3.2.1 Improving soil depth models by incorporating NSW data

Depth class Stem shape and taper were significant predictors of soil depth class. Parameters in the final model were shape, taper and region (Table 6.4). The model describes a consistent relationship between shape and taper across all four regions (Figure 6.5). In each region, deeper soils were associated with increasing rates of taper and higher values of stem shape. The predicted range of taper values over which the transition from shallow to deep depth classes occurs is higher for the ACT site than for either the SA or NSW sites;

suggesting as mentioned previously, that the model requires calibration for each region to which it is applied.

Table 6.4 Regression statistics for logistic regression of soil depth class on stem shape (*b*) and taper (*k*) for ACT, TAS, SA and NSW case study sites.

Whole model test

Model	-Log Likelihood	DF	χ^2	$P > \chi^2$
Difference	18.37	5	36.73	< 0.0001
Full	48			
Reduced	66.36			
Logit R^2	0.28			
Observations	97			

Parameter estimates

Coefficient	β	SE β	χ^2	$P > \chi^2$
Intercept	17.73	5.98	8.78	0.003
Region [ACT]	5.83	1.57	13.73	0.0002
Region [NSW]	2.25	0.64	12.34	0.0004
Region [SA]	-3.86	1.02	14.27	0.0002
Region [TAS]	-4.22	.	.	.
b	3.06	0.67	20.69	< 0.0001
k	-23.26	5.68	16.77	< 0.0001

Prediction formula:

$$Prob[Shallow] = \frac{1}{1 + e^{Ln[Deep]}}$$

where $Ln[Deep] = 17.73 + Region + 3.06 * b + (-23.26) * k$

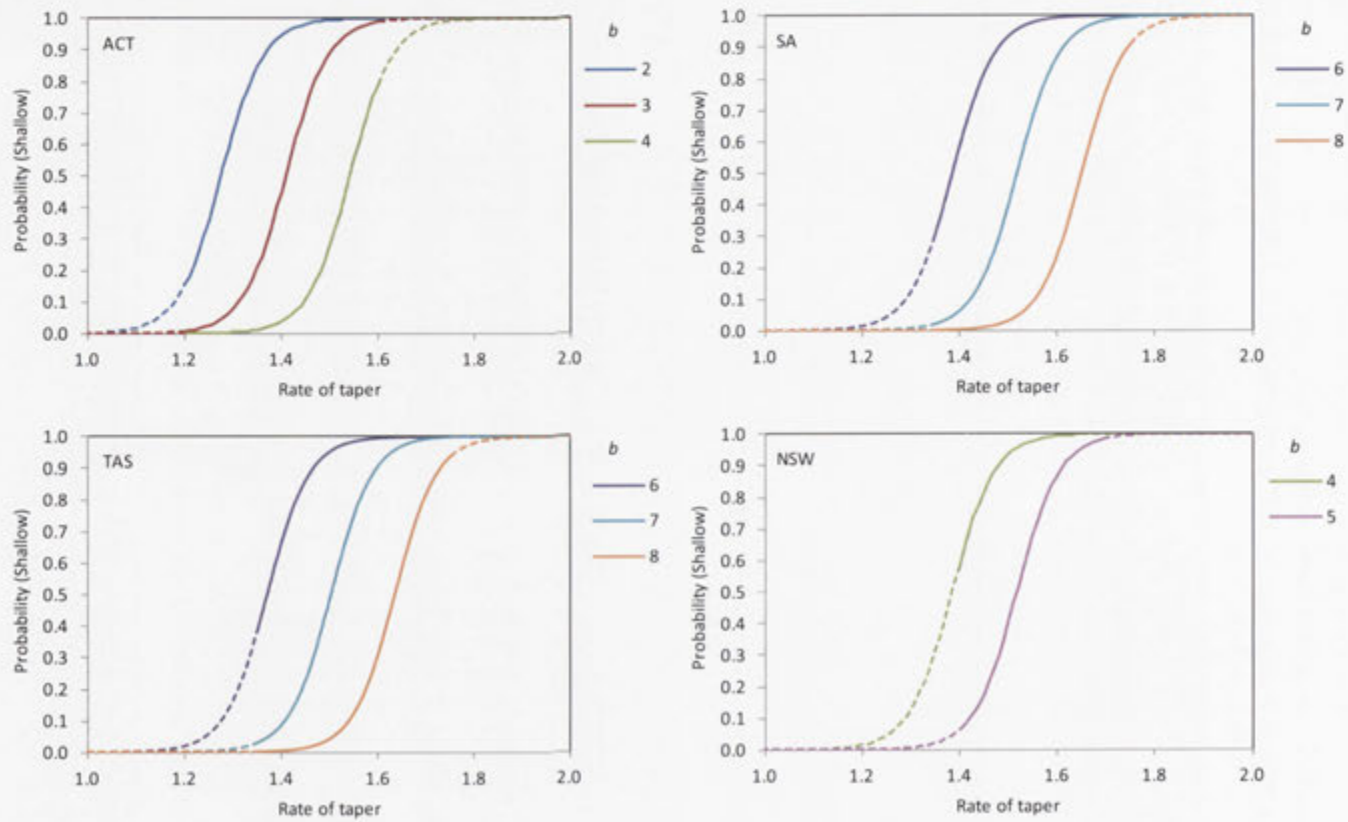


Figure 6.5 Prediction profiles for the logistic regression of soil depth class on stem shape and taper for ACT, TAS, SA and NSW case study sites. *Solid lines denote interpolated values and perforated lines denote extrapolated values.*

Individual tree height was a highly significant ($p < 0.05$) predictor of soil depth class. Parameters in the final form of the model were individual tree height and region (Table 6.5). Deeper soils were associated with taller trees at ACT, TAS, SA and NSW case study sites (Figure 6.6).

Table 6.5 Regression statistics for logistic regression of soil depth class on individual tree height for ACT, TAS, SA and NSW case study sites.

Whole model test

Model	-Log Likelihood	DF	χ^2	$P > \chi^2$
Difference	21.74	4	43.47	< 0.0001
Full	38.9			
Reduced	60.63			

Logit R^2	0.36
Observations	88

Parameter estimates

Coefficient	β	SE β	χ^2	$P > \chi^2$
Intercept	-21.12	4.42	22.83	< 0.0001
Region [ACT]	6.95	1.59	18.96	< 0.0001
Region [NSW]	3.00	0.78	14.87	0.0001
Region [SA]	-4.13	1.06	15.31	< 0.0001
Region [TAS]	-5.82	.	.	.
Height	1.06	0.22	23.15	< 0.0001

Prediction formula:

$$Prob[Shallow] = \frac{1}{1 + e^{\ln[Deep]}}$$

where $Ln[Deep] = -21.12 + Region + 1.06 * Height$

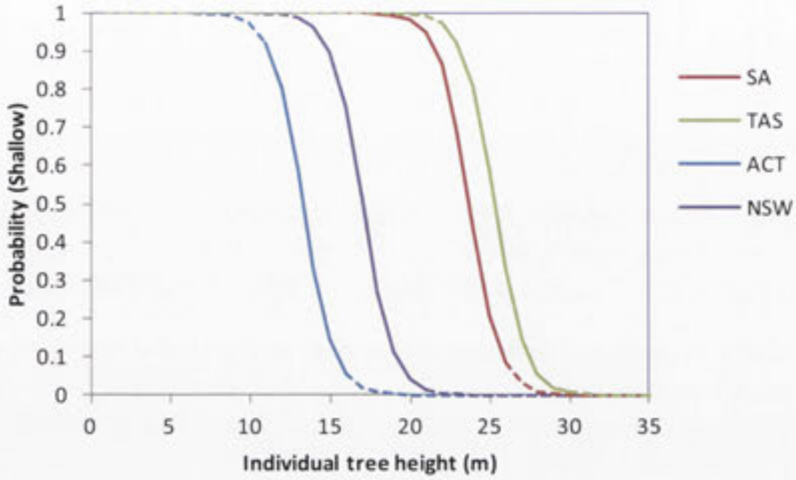


Figure 6.6 Prediction profiles for the logistic regression of soil depth class on individual tree height for ACT, TAS, SA and NSW case study sites. *Solid lines denote interpolated values and perforated lines denote extrapolated values.*

Absolute soil depth Individual tree height was a significant predictor of absolute soil depth but residuals were poorly distributed and heterogeneous. Graphical analysis of the normal-quantile plot also indicated the distribution was non-normal. Natural log transformation of depth resolved the problem of heterogeneity and marginally reduced non-normality. A significant model ($p < 0.05$) was obtained. Back transformation was performed and a correction factor (Snowdon's) applied to correct estimates for the bias introduced by the transformation (Table 6.6).

Stem shape and taper were significant predictors of absolute soil depth with well distributed residuals. The incorporation of additional data from NSW resulted in the interaction term dropping out from the original model developed in SA.

Table 6.6 Regression statistics for the multiple regression of soil depth class on individual tree height for SA and NSW case study sites.

Summary of fit

R^2	0.48
RMSE	0.45
Observations	56

Analysis of variance

Source of variation	DF	SS	MS	F-ratio	Prob > F
Model	2	10.02	5.01	24.58	< 0.0001
Error	53	10.80	0.20		
Total	55	20.81			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob > |t|
Intercept	-3.41	0.61	-5.62	< 0.0001
Region [NSW]	0.67	0.10	6.94	< 0.0001
Region [SA]	-0.67	0.10	-6.94	< 0.0001
Height	0.17	0.03	5.92	< 0.0001

Prediction formula:

$$Ln(Depth) = -3.41 + Region + 0.17 * Height$$

Prediction formula (back transformed with bias correction):

$$Depth = e^{-3.41 + Region + 0.17 * Height} * \frac{1.50}{1.36}$$

Parameters in the final SA and NSW model were shape, taper and region (Table 6.7). The model describes a consistent relationship between stem shape and taper in the butt swell section and absolute soil depth in NSW and SA. Residuals showed no evidence of non-normality or unequal variance. At both sites, depth increased with decreasing rates of taper and higher values of stem shape. Model predictions of depth were approximately 1 m deeper on average at the NSW site than at the SA site for the same values of shape and taper, reflecting the generally deeper soils of the NSW region (Figure 6.7). The model would require calibration to account for regionally-specific factors.

Table 6.7 Regression statistics for the multiple regression of soil depth class on stem shape (*b*) and taper (*k*) for SA and NSW case study sites.

Summary of fit

R^2	0.39
RMSE	0.67
Observations	64

Analysis of variance

Source of variation	DF	SS	MS	F-ratio	Prob > F
Model	3	16.89	5.63	12.68	< 0.0001
Error	60	26.64	0.44		
Total	63	43.53			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob > |t|
Intercept	3.90	2.17	1.79	0.078
Region [NSW]	0.96	0.16	5.88	< 0.0001
Region [SA]	-0.96	0.16	-5.88	< 0.0001
b	0.78	0.16	5.02	< 0.0001
k	-4.74	1.58	-3.00	0.004

Prediction formula:

$$Depth = 3.90 + Region + 0.78 * b - 4.74 * k$$

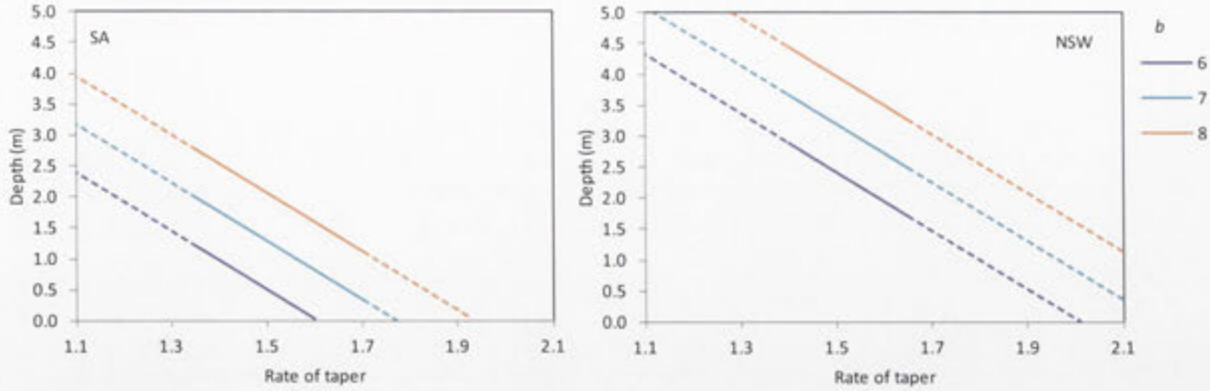


Figure 6.7 Predicted soil depth for the multiple regression of absolute soil depth on stem shape (b) and taper (k) for SA and NSW case study sites. *Solid lines denote interpolated values and perforated lines denote extrapolated values.*

Model evaluation The depth class model fitted using the total number of observations performed better than the cross-validated depth class model based on n - 1 observations (Table 6.8). The $n - 1$ model shows that using only the precision estimates from the original (full) model was an over-optimistic estimation of the predictive power of the model.

Table 6.8 The observed and predicted frequencies for the a) full and b) cross-validated (*n* – 1) depth class model and the results of significance tests.

a) Contingency table

Observed	Predicted		% Correct
	Deep	Shallow	
Deep	47	15	75.81
Shallow	8	27	77.14
Overall % correct			76.29

Significance tests

Test	χ^2	$P > \chi^2$
Likelihood ratio	26.49	< 0.0001
Pearson	25.56	< 0.0001

n	97
DF	1
-Log Likelihood	13.24
Logit R^2	0.2

b) Contingency table

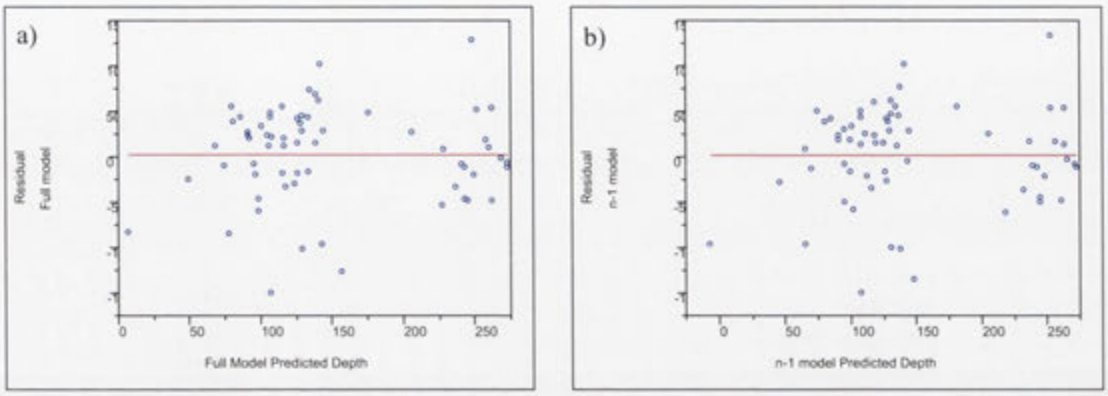
Observed	Predicted		% Correct
	Deep	Shallow	
Deep	42	13	76.36
Shallow	17	25	59.53
Overall % correct			69.1

Significance tests

Test	χ^2	$P > \chi^2$
Likelihood ratio	13.04	0.0003
Pearson	12.87	0.0003

n	97
DF	1
-Log Likelihood	6.52
Logit R^2	0.1

The mean and RMSE of residuals were similar for the full and cross-validated model (Figure 6.8). Ideally, the mean of residuals should equal zero, which indicates a stable model that is not greatly affected by any single point. In this case, the difference from zero is extremely small relative to the RMSE and could be considered not different from zero. RMSE values were similar for both models and were therefore accepted as unbiased estimates.



	Full model	*n* - 1 model
Mean	2.67	2.13
RMSE	52.08	53.58

Figure 6.8 Distribution of residuals for a) full and b) cross-validated absolute soil depth model.

6.3.2.2 Examining the two-way relationship between shape and taper in the butt swell section and soil properties

Using stem shape and taper in the butt swell to predict soil properties A number of significant relationships were identified between soil variables and tree attributes at both study sites. Overall, a greater number of significant relationships were identified at Green Hills (12) than at Carabost (9). Different soil variables were significant at each site. At Green Hills, stem shape, taper or height were more often significantly related to A horizon soil variables than B horizon soil variables (Table 6.9). Stem shape and taper were related to both available nitrogen and total organic carbon but tree height was significantly related to the greatest number of soil variables including, the depth of the A horizon, available water holding capacity, electrical conductivity (EC), total organic carbon and total nitrogen. For both the A and B horizons at Green Hills, the strongest correlation identified was that between stem taper and available N. At Carabost there was no difference in the number of significant relationships identified for A and B horizon soil variables (Table 6.10). There were no significant relationships between stem taper and any A horizon soil variable, but stem shape was significantly related to a number of A horizon variables including: available water holding capacity, labile phosphorus (inorganic loosely bound phosphorus compounds) and total organic carbon. Stem shape, taper and height were all significantly related to the depth of the B horizon.

Table 6.9 Correlation coefficients (r) of selected soil variables grouped by soil horizon for stem shape (b), taper (k) and height at Green Hills (critical $r = 0.35$, $n = 30$). *Values in bold denote significant at p = 0.05.*

Soil horizon	Soil variable	*b*	*k*	Height
A	Depth of horizon	-0.1095	0.2024	**-0.3679**
	Water holding capacity	**-0.4279**	-0.0192	**-0.5876**
	Total organic carbon	**-0.4566**	**-0.4386**	**-0.5003**
	Total P	-0.0915	-0.1283	0.1182
	Labile P	0.0429	-0.1015	0.2794
	Plant available P	-0.0227	-0.0751	0.2018
	Total N	-0.3168	-0.2721	**-0.4405**
	Plant available N	**0.5178**	**0.7264**	0.235
	pH	-0.0193	0.1051	-0.0323
	EC	-0.0577	0.0549	**-0.3468**
B	Depth of horizon	-	-	-
	Water holding capacity	0.2213	-0.0087	0.2195
	Total organic carbon	**-0.515**	-0.4804	-0.3339
	Total P	0.0729	-0.1666	**0.4796**
	Labile P	0.06	0.1053	0.2029
	Plant available P	0.1366	0.1409	0.2664
	Total N	-0.2504	-0.2771	-0.0534
	Plant available N	-0.3043	**-0.5273**	0.0127
	pH	0.0034	-0.0352	0.1793
	EC	-0.1222	-0.1196	0.0233

Table 6.10 Correlation coefficients (r) of selected soil variables grouped by soil horizon for stem shape (b), taper (k) and height at Carabost (critical $r = 0.43$, $n = 19$). *Values in bold denote significant at p = 0.05.*

Soil horizon	Soil variable	*b*	*k*	Height
A	Depth of horizon	0.1582	0.3746	**-0.0932**
	Water holding capacity	**0.4377**	0.2194	**0.3611**
	Total organic carbon	**-0.4723**	**-0.1502**	**-0.2766**
	Total P	-0.2272	0.2889	-0.4812
	Labile P	-0.6433	-0.2655	-0.3932
	Plant available P	-0.0011	0.4117	-0.3029
	Total N	-0.2935	0.1874	**-0.463**
	Plant available N	**0.0583**	**0.1558**	-0.1187
	pH	0.0309	-0.2862	0.2396
	EC	-0.2648	0.1556	**-0.3414**
B	Depth of horizon	0.5111	0.478	0.4843
	Water holding capacity	0.2288	0.0899	0.4216
	Total organic carbon	**-0.4596**	-0.3888	-0.205
	Total P	0.3148	0.4332	**0.0628**
	Labile P	-0.1497	0.1469	-0.4146
	Plant available P	0.2729	0.2347	0.2575
	Total N	-0.2408	-0.1166	-0.3015
	Plant available N	-0.0892	**-0.2015**	0.1572
	pH	0.3057	0.3129	0.1347
	EC	-0.2573	-0.423	0.2072

Very few of the possible relationships identified were significant in a simple linear regression. At Green Hills, stem taper was a significant predictor of available nitrogen in the A horizon ($r = 0.72$, $r^2 = 0.53$, $n = 10$, $p < 0.05$) with an acceptable residual distribution (Table 6.11). Neither stem shape, taper nor height were significant predictors of any other soil variable identified. At Carabost, stem shape was a significant predictor of total organic carbon and labile phosphorus in the A horizon, but the residuals were poorly distributed. Tree height was a significant predictor of total phosphorus in the A horizon with an acceptable residual distribution ($r = -0.48$, $r^2 = 0.23$, $n = 18$, $p < 0.05$).

Table 6.11 Regression statistics for the simple linear regression of available nitrogen in the A horizon on stem taper (k) for Green Hills case study site.

Summary of fit	
R^2	0.52
Root mean square error	2.08
Observations	10

Analysis of variance

Source of variation	**DF**	**SS**	**MS**	**F ratio**	**Prob>F**
Model	1	38.71	38.71	8.93	0.01
Error	8	34.65	4.33		
Total	9	73.36			

Parameter estimates

Coefficient	**β**	**SE β**	**t-ratio**	**Prob > |t|**
Intercept	-84.16	29.12	-2.89	0.02
k	59.14	19.78	2.89	0.01

Using soil properties to predict stem shape and taper in the butt swell At the Green Hills site, combinations of A horizon soil variables were significant predictors of both shape and taper in separate multiple regression models. At Carabost, combinations of B horizon soil properties were generally not significant predictors of shape or taper and neither were combinations of both A and B horizon soil variables.

Parameters in the models selected for Green Hills were depth of the A horizon, water holding capacity, electrical conductivity, total organic carbon, and total and available nitrogen (Tables 6.12 and 6.13). Residuals were well distributed, satisfying assumptions of normality and homogeneity of variance. However, given the small sample size and the number of parameters fitted, it is likely that the model is over-fitted. Although the data fits the model well, more data would be required to test the adequacy of the model.

Table 6.12 Regression statistics for the multiple regression of selected A horizon soil properties on stem shape (*b*) for the Green Hills case study site.

Summary of fit

R^2	0.97
Root mean square error	0.13
Observations	10

Analysis of variance

Source of variation	DF	SS	MS	F ratio	Prob > F
Model	6	2.17	0.36	21.19	0.015
Error	3	0.05	0.02		
Total	9	2.23			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob > |t|
Intercept	5.94	0.31	18.95	< 0.001
Depth of A horizon	0.32	0.05	6.81	0.006
Water holding capacity	-0.21	0.03	-8.01	0.004
Electrical conductivity	0.04	0.01	5.08	0.01
Total organic carbon	0.51	0.12	4.36	0.02
Total nitrogen	-46.8	7.9	-5.92	0.01
Available nitrogen	0.05	0.02	3.03	0.06

Table 6.13 Regression statistics for the multiple regression of selected A horizon soil properties on taper (k) for the Green Hills case study site.

Summary of fit

R^2	0.99
Root mean square error	0.002
Observations	10

Analysis of variance

Source of variation	DF	SS	MS	F ratio	Prob > F
Model	6	0.011	0.001	286.29	< 0.001
Error	3	< 0.001	< 0.001		
Total	9	0.011			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob > |t|
Intercept	1.42	0.006	233.81	< 0.001
Depth of A horizon	0.02	< 0.001	22.76	< 0.001
Water holding capacity	-0.01	< 0.001	-21.69	< 0.001
Electrical conductivity	0.003	< 0.001	20.51	< 0.001
Total organic carbon	0.03	0.002	12.65	< 0.001
Total nitrogen	-2.98	0.03	19.45	< 0.001
Available nitrogen	0.006	0.005	16.78	< 0.001

6.4 Discussion

Stem shape and taper were significant predictors of depth class and absolute soil depth. The addition of NSW data to depth class and absolute depth models produced slight changes to prediction profiles of both models. Inclusion of the NSW data in the depth class model sharpened the transition between deep (where probability = 0) and shallow (where probability = 1) soil depth classes. A sharper transition over a shorter range of tapers improves the discriminating power of the model by minimising the range of values over which the probability of a deep or shallow soil class is less clear (e.g. probabilities in the range of 0.4 - 0.6).

The addition of NSW data to the preliminary absolute depth model developed in SA influenced model predictions of soil depth. In the preliminary absolute depth model, predictions for the range of measured values converged at a depth of 0.05 m (Chapter 5, Section 5.3.3). However, the addition of new data removed this effect. Plots were parallel, even when extrapolated beyond the range of measured values. This may indicate that the convergence at 0.5 m depth in the previous model may have been an artefact of a small sample size. However, this may warrant further investigation in future work as Lewis et al. (1976) note a critical threshold at these shallow depths for predicting site quality in South Australia.

Prediction profiles of depth class models were similar between some sites. The range of tapers over which the transition between deep to shallow soil depth classes occurred was 1.2 - 1.6 cm/m for both SA and TAS and 1.4 - 1.8 cm/m for both ACT and NSW. Although each site differs considerably in terms of site and soil characteristics, these similarities may suggest that certain soil variables may be the dominant factor influencing the relationship at each site. This could be soil depth at SA and TAS sites, where soils are relatively deep. Soil depth could also be the dominant influencing factor at ACT and NSW sites where soils are relatively shallow but in this case only soils at the Carabost site in NSW were shallow. Understanding the environmental factors influencing the relationship at each region is not within the scope of this thesis and more data would be required. However, it is clear that models require calibration to the region of interest to account for these differences.

A significant model for individual tree height was obtained, but only after log transformation resolved issues of heterogeneity and non-normality in the regression. The need to use transformations to satisfy the assumptions of the regression introduced an additional level of complexity to model development. As this research aims to develop simple models of soil depth, the need for transformations would reduce the potential utility of individual tree height.

No practically useful relationships between stem shape and taper in the butt swell section of the stem and other soil properties could be established across the two NSW sites from the data collected. The relationship between stem taper and available N in the A horizon for Green Hills was statistically significant, but the relationship was not strong enough to warrant further model development. Significant soil variables were usually those in the surface A horizon, which represents the region of the soil profile with the greatest abundance of nutrients, carbon and soil moisture for exploitation by tree roots. Neither shape nor taper were useful predictors of any individual soil variable. Combinations of soil variables in the A horizon, appeared to be significant predictors of stem shape and taper in a multiple regression for the Green Hills site.

While the model appears to fit the available data well, it is recognised that the models have been considerably overparameterised for the small size of the dataset (10 observations). In addition, it is likely that the soil properties are highly correlated with one another introducing a problem with multiple collinearity. For these reasons, any conclusions must be tentative. Although there is sufficient evidence to suggest that soil nutrients have an effect on the shape of the butt swell, much more data would be required to quantify a relationship and parameterise a model.

In Waterworth's (2009) model of stem shape dynamics, the complexity of the relationship between shape and crown resources was simplified by grouping all resources influencing cell growth together as 'photosynthates'. The ability of the tree to use photosynthates was constrained by thresholds of water availability, minimum temperature and other limits. Hence, clarifying the nature of the relationship between stem shape, taper and soil resources requires knowledge of which soil variables define the resources pool for tree growth at a specific site and which individual or combinations of interacting variables are the strongest determinants of growth in the basal 2 m of the tree stem. Soil depth could be used as a general index but it may be constrained by limiting thresholds of specific soil variables such as water, nutrients or carbon. For this reason, the models obtained in this case study were complex and not consistent across the two sites. The suite of significant soil parameters in the model developed for Green Hills may be the dominant thresholds for that particular site, but not for other sites, such as for Carabost where similar combinations of soil parameters were not significant predictors of either shape or taper. The soil variables measured may not be limiting at that site or may be present in such abundance that they exceed the threshold. In both these instances, variations in individual or combinations of soil resources would not likely be expressed in the tree by changes in shape or taper.

6.5 Summary and conclusions

The addition of the NSW dataset confirmed that parameter estimates are regionally specific. However, because the direction of the relationship between soil depth and stem shape and taper is constant, the relationship is generalisable across a range of site and soil conditions for *P. radiata*. A model based on individual tree height required transformation to resolve issues of heterogeneity and non-normality. The practical utility of individual tree height at the NSW site was reduced by the greater sophistication of the model required compared with stem shape and taper in the butt swell.

No practically useful relationships could be established with other soil properties. It was possible to predict simple linear relationships, such as that between available nitrogen and taper, but more powerful relationships or multiple linear models could not be successfully fitted. This was likely due to the small sample size and interactions between variables.

A range of soil properties were significant predictors of stem shape and taper in a multiple regression. However, the model was overparameterised due to the number of parameters fitted and the limited size of the dataset; this, together with issues of multiple collinearity mean that any conclusions must be purely speculative. More data would be required to clarify the relationship and develop a better understanding of the below-ground resource pool that defines tree growth at a particular site.

Chapter 7: Extending the model to subtropical pine and improving spatial mapping of soil depth

7.1 Introduction

The preceding chapters of this thesis have demonstrated that the relationship between stem shape and taper in the butt swell section of the stem and soil depth is consistent and general across different regions in southern Australia for *P. radiata*. In general, deeper soils were associated with increasing shape and decreasing rates of taper. This was observed in all regions, ranging from the shallow soils of the ACT to the relatively deep soils of SA, NSW and Tasmania. Two simple models for predicting soil depth were developed based on this relationship: one for predicting depth class and the other for predicting absolute soil depth. The models were developed and improved with the incremental addition of data collected from each region. As regional factors influence the predicted values of shape and taper, models must be calibrated for the region to which it is applied.

The model has been developed for several regions but, thus far, limited only to *P. radiata* and the sites on which it is grown in southern Australia. The work reported in this chapter investigates whether the relationship found for *P. radiata* in southern Australia is applicable to a different species of pine growing in sub-tropical climates, and a number of related questions outlined below. This stage of the research was undertaken in Toolara State Forest, a plantation estate planted with a hybrid between two subtropical pines, *Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis*, on the coastal lowlands of subtropical Queensland. The study site was previously the subject of a paired catchment study of the hydrology of these pine plantations conducted by Bubb and Croton (2002) over a 10 year period. The work of Bubb and Croton (2002) was used as a guide for the sampling approach of the work reported here, but was not otherwise used.

This stage of research had several main objectives. The first was to investigate whether the relationship between shape and taper and soil depth established for *P. radiata* in southern Australia is generalisable to other examples of the *Pinus* genus in environments with different rainfall patterns, soil development and management history. The hybrid subtropical pine, *Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis*, in the Queensland coastal lowlands is a commercially important pine and appropriate for this expanded study. Assuming the general relationship found for *P. radiata* does hold for the Queensland hybrid, the second objective was to parameterise a regression model for predicting soil depth using the individual tree shape and taper data collected from this study site. A final objective, which represents an additional step of work not conducted elsewhere, was to investigate the practical or operational application of the tree-based model for mapping within-compartment soil depth variation using the Queensland study site as the test location.

Given the multiple objectives of this case study, the chapter is divided into four sections. The first section comprises the general description of the study area, general methods and results of the preliminary data exploration. The second section describes the development of the tree-based model and the third section describes the application of the tree-based model to the Queensland study area. The chapter concludes with an overall discussion of the development and application of the tree-based model.

7.2 Study area

7.2.1 Location and description of sample site

Sampling was conducted in hybrid *Pinus elliottii* var. *elliottii* x *P. caribaea* var. *hondurensis* plantations at Toolara State Forest (26° 02″ S, 152° 52″ E), located approximately 200 km north of Brisbane, Queensland (Figure 7.1). Sample sites were located in a study area approximately 200 ha in size.

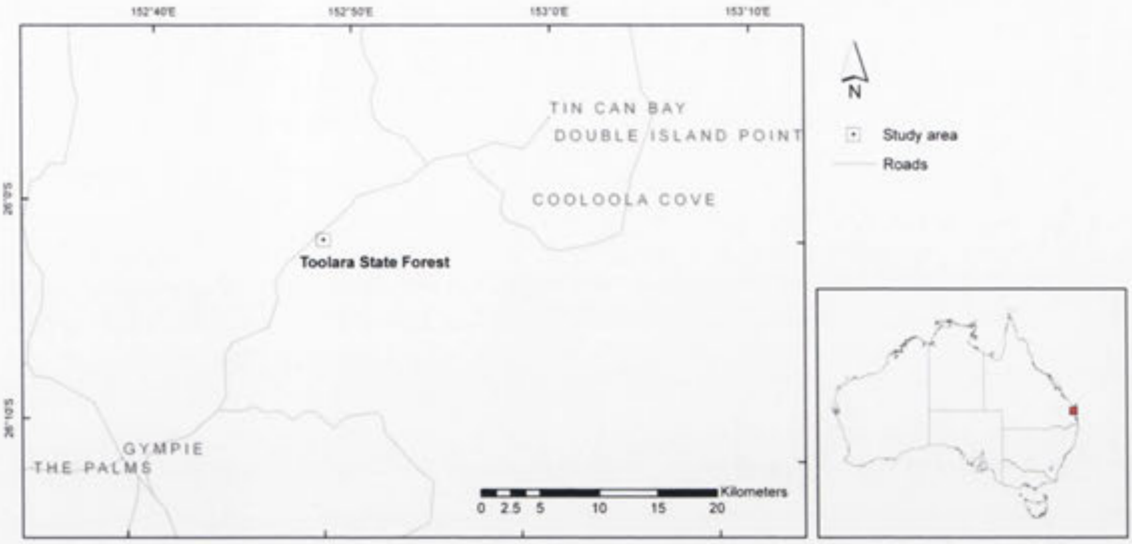


Figure 7.1 Location of sample sites in Toolara State Forest, QLD.

The Toolara region has a subtropical climate with an average annual rainfall of 1302 mm and mean air temperatures ranging between 13.6 °C during winter and 26.4 °C during summer. The topography is flat to gently inclined, with an elevation of approximately 60 m. Soils are derived from undifferentiated Mesozoic sandstone sediments. The study site encompasses two adjacent catchments: Crayfish (140 ha) and Review (62 ha). An ephemeral stream in each catchment is the main surface drainage feature; streams are characterised by shallow waterholes along their length for much of the year (Bubb and Croton 2002). Topographic slope is less than 1 % for both catchments.

Soils on lower slopes tend to be shallow, poorly drained lateritic, gradational and gleyed Podosols. These are also regularly affected by extended periods of water-logging, due to periodic heavy rains and the presence of a restrictive layer of low permeability or aquitard that is situated at depths ranging from 0.5 to 10 m. The thickness of this layer ranges from at least 2 m to more than 10 m. Soils on upper slopes are relatively well-drained and dominant soil types are red or yellow Chromosols and Kandosols. A typical soil profile consists of a free-draining loamy sand A horizon, between 0.3 and 0.5 m thick, overlying a sand clay loam B horizon, which may extend to depths of 1.0 - 1.5 m. These overlie a C horizon of light medium clay which extends down to a clay layer of low permeability or aquitard. The average depth of the soil profile above the aquitard layer is approximately 1.1 m at Crayfish and 1.5 m at Review. Detailed measurements of soil depth have been recorded across the two catchments as a result of previous work by Bubb and Croton (2002).

Compartments are second rotation plantings and consist of a hybrid of *Pinus elliottii* var. *elliottii* x *P. caribaea* var. *hondurensis*. Understorey vegetation was abundant at this site.

Vegetation consisted of a range of species including *Imperata Cylindrica*, wildling *Pinus* and *lantana camara* on upper slopes, and *Melaleuca spp*, *Acacia spp*, *Jacksonia scoparia* and *Eucalyptus robusta* in lower slopes and drainage lines. Prior to plantation establishment, the site was native open woodland dominated by *Melaleuca quinquinervia* and *Angophora woodsiana*, with an understorey of *Banksia robur* and *Hakea gibbosa*.

7.3 General methods

7.3.1 Sampling design

The distribution of sampling points across the study area followed the sampling design of Bubb and Croton (2002). Sample plots were located in six adjacent plantation compartments of three age classes. Due to the limited size of the study area, all compartments in the area were sampled which encompassed several age classes. Sample plots were positioned along straight-line transects about 0.5 km in length at regular intervals of 50 m. Transects crossed at a point perpendicular to the main drainage line in each catchment.

7.3.2 Measurement of soil and trees

Each plot comprised of 6 trees. At each plot, tree heights and stem shape and taper in the bottom 2 m of the tree were measured using the general methods outlined in Chapter 3 (Section 3.4.4). Soil samples were collected at a single point in the centre of each plot using an auger. Soil depths were measured down to the aquitard or to a maximum depth of 2.0 m. Soils were sampled at every second plot (intervals of 100 m) due to the relatively flat topography of the study area.

7.3.3 Data exploration

The distributions of shape, taper and tree height were examined using box-plots and histograms, as described in Chapter 3, Section 3.5. A two sided independent sample t-test was used to test for significant ($p < 0.05$) relationships between stem shape parameters and both soil depth class and absolute soil depth. As soils were shallower on average at this site than the others, a threshold depth of 1.0 m, as chosen for samples in South Australia (Chapter 5), would assign the majority of sample plots to the shallow depth class. Threshold depths above and below 0.7 m resulted in no plots being allocated to either shallow or deep classes for one or more age classes. Hence, a threshold depth at 0.7 m was selected to ensure plots were allocated to both shallow and deep depth classes within each age class. Sensitivity analysis indicated that results were not sensitive to changes in the threshold depth between a range of 0.5 and 0.8 m.

7.4 Results

7.4.1 Data exploration

The study area encompassed three age classes ranging from 7 to 15 years. As there were significant differences in stem shape, taper and height with age class (Table 7.1), the data were stratified by age class for exploratory data analyses.

Mean tree height and diameter increased with tree age but for all age classes, mean stem shape in the basal 2 m of the tree was neiloidal, with an average taper of about 1.4 cm/m (Table 7.2). There were no significant differences in stem shape, taper or height with change in soil depth class for trees in all age classes (Figure 7.2, Table 7.3).

Table 7.1 Differences in stem shape (*b*), taper (*k*) and height between age classes for QLD case study site.

Parameter	Age class	n	Mean (SE)	*p*-value*	Mean difference	95 % Confidence Interval
b	7	28	3.16 (0.09)	0.001	-0.58	[-0.91, -0.25]
	11	10	3.74 (0.11)			
k	7	28	1.43 (0.02)	0.34	0.03	[-0.03, 0.10]
	11	10	1.39 (0.02)			
Height	7	28	13.3 (0.19)	< 0.001	-2.63	[-3.35, -1.91]
	11	10	15.9 (0.28)			
b	11	10	3.74 (0.11)	0.75	-0.06	[-0.45, 0.33]
	15	17	3.80 (0.13)			
k	11	10	1.39 (0.02)	0.07	0.05	[-0.1, 0.12]
	15	17	1.34 (0.02)			
Height	11	10	15.9 (0.28)	< 0.001	-4.44	[-5.14, -3.75]
	15	17	20.4 (0.20)			
b	7	28	3.16 (0.09)	< 0.001	-0.64	[-0.94, -0.33]
	15	17	3.80 (0.13)			
k	7	28	1.43 (0.02)	< 0.001	0.08	[0.03, 0.14]
	15	17	1.34 (0.02)			
Height	7	28	13.3 (0.19)	< 0.001	-7.07	[-7.65, -6.49]
	15	17	20.4 (0.20)			

Table 7.2 Mean stem shape and taper in the basal 2 m of the stem, tree height and other sample characteristics for each age class at the QLD case study site. *Bracketed values denote the standard deviation.*

	Age*		
	7 years	**11 years**	**15 years**
Thinning	Unthinned	Unthinned	Unthinned
Plot size (individual trees)	6	6	6
Sample size (plots)	28	10	17
Mean DBH (cm)	17.74 (1.34)	21.65 (1.67)	24.68 (1.54)
Mean height (m)	13.3 (0.99)	15.9 (0.87)	20.4 (0.83)
Mean stem shape	3.16 (0.46)	3.74 (0.36)	3.80 (0.53)
Mean taper	1.43 (0.10)	1.39 (0.05)	1.34 (0.08)

*at time of measurement

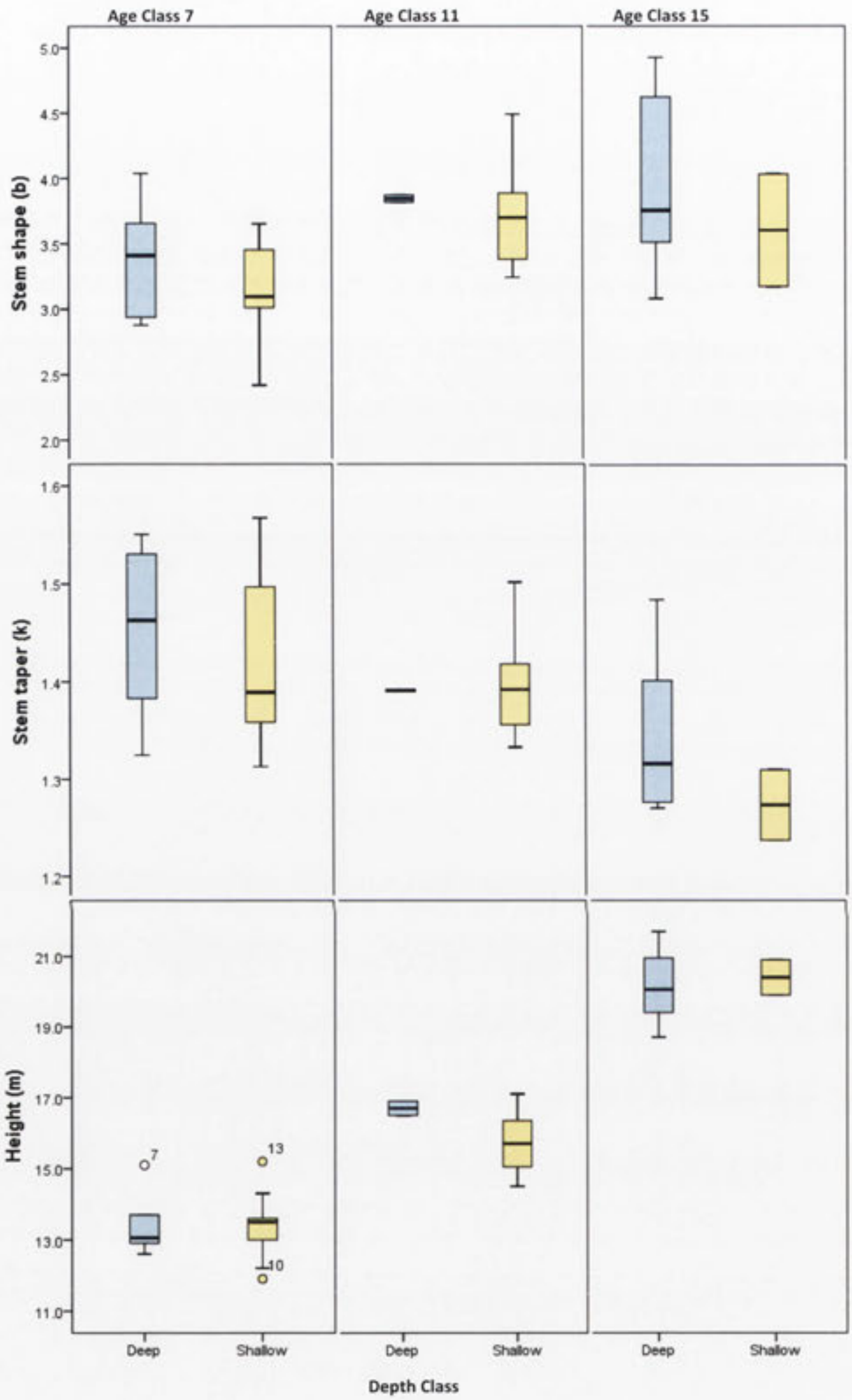


Figure 7.2 Boxplots of stem shape, taper and height grouped by soil depth class for QLD case study site.

Table 7.3 Differences in stem shape (*b*), taper (*k*) and height with change in soil depth class for each age class at QLD case study site.

Age (years)	Parameter	Depth class	n	Mean (SE)	p-value*	Mean difference	95 % Confidence Interval
7	b	Deep	6	3.39 (0.16)	0.24	-0.25	[-0.69, 0.20]
		Shallow	10				
	k	Deep	6	1.45 (0.04)	0.55	-0.03	[-0.13, 0.07]
		Shallow	10				
	Height	Deep	6	13.40 (0.38)	0.97	-0.02	[-1.06, 1.02]
		Shallow	10				
11	b	Deep	2	3.85 (0.26)	0.67	-0.14	[-0.82, 0.55]
		Shallow	8				
	k	Deep	2	1.39 (0.04)	0.91	0.005	[-0.09, 0.10]
		Shallow	8				
	Height	Deep	2	16.7 (0.58)	0.17	-0.98	[-2.47, 0.52]
		Shallow	8				
15	b	Deep	8	3.97 (0.22)	0.54	-0.27	[-1.23, 0.69]
		Shallow	3				
	k	Deep	8	1.34 (0.03)	0.3	-0.05	[-0.17, 0.06]
		Shallow	3				
	Height	Deep	8	20.15 (0.33)	0.78	0.18	[-1.26, 1.62]
		Shallow	3				

* p-value based on a 2-sided independent sample t-test

There were no significant differences in stem shape, taper or height with change in soil depth class within age classes. Hence, no significant models for depth class were found for the QLD case study site. As the sample size was relatively small, further dividing the data into depth classes resulted in too much residual error for any significant differences between depth classes to be detected, i.e. variation within depth classes was as great as variation between depth classes. However, stem shape and taper, and individual tree height were significant predictors of absolute soil depth. The following sections describe the development and application of the absolute soil depth models.

7.5 Selection and development of absolute depth models

Stem shape and taper were significant ($p < 0.05$) predictors of soil depth in a multiple regression, while individual tree height was a significant predictor of soil depth in a simple linear regression. This section describes the development and parameterisation of the two models.

7.5.1 Methods

Model parameters were selected by fitting the full factorial model and removing non-significant highest order interactions preferentially, until a reduced model with all significant ($p < 0.05$) parameters was found. Model parameters tested included age class, shape, taper and individual tree height.

7.5.2 Results

Parameters in the final form of the stem shape and taper model were shape (b), taper (k), and the reciprocal of taper ($1/k$) (Table 7.4). Age class and other interactions were not significant. A near-outlying point identified in box and whiskers plots as having an unusually low value of k was examined and found to not significantly influence the parameter estimates of the final model. However, this point added substantial variation to the data and its removal reduced the RMSE by 9.5 % and improved the R^2 by more than 10 %. Residuals were also well distributed and showed no evidence of non-normality, unequal variance or nonlinearity. Thus, this point was removed from further analysis.

Table 7.4 Regression statistics for the multiple regression of soil depth on stem shape and taper for QLD case study site.

Summary of fit

R^2	0.37
RMSE	0.20
Observations	36

Analysis of variance

Source of variation	DF	SS	MS	F ratio	Prob > F
Model	3	0.71	0.24	6.19	0.002
Error	32	1.22	0.04		
Total	35	1.93			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob > |t|
Intercept	-67.74	18.81	-3.6	0.001
b	0.14	0.06	2.3	0.03
k	23.67	6.65	3.56	0.001
1/k	48.51	13.25	3.66	< 0.001

Prediction formula:

$$Depth = -67.74 + 0.14 * b + 23.67 * k + 48.51 * \frac{1}{k}$$

Consistent with the trend found for *P. radiata*, the shape of the butt swell section increases with increasing soil depth while taper decreases with increasing depth, but only for lower values of k (Figure 7.3). The relationship between taper and depth is curvilinear at this site, which necessitates the inclusion of a reciprocal taper parameter in the model to remove heterogeneity in the residuals. For the selected values of shape in Figure 3.25, minima are reached at a depth of about 0.5 m. The range of model predictions of soil depth (0.4 - 1.3 m) was about equivalent to the range of observed soil depths (0.1 - 1.2 m).

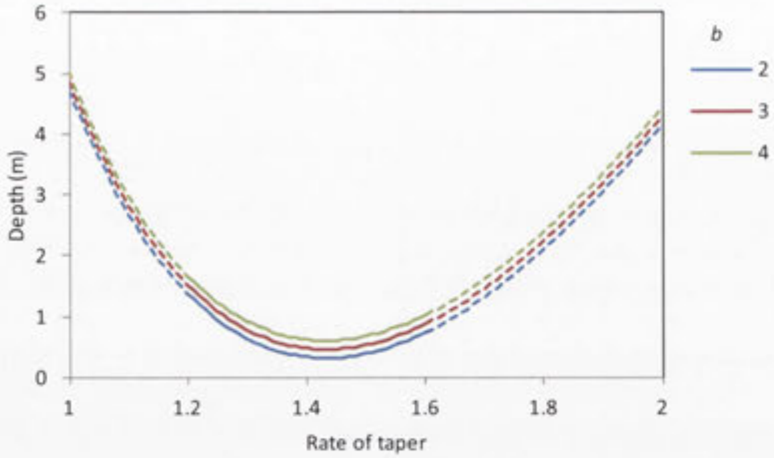


Figure 7.3 Predicted soil depth for the multiple regression of soil depth on stem shape (*b*) and taper (*k*) for the QLD case study site.

Individual tree height alone was a significant predictor of absolute soil depth in a simple linear regression with an acceptable error distribution (Table 7.5). Age class was not a significant parameter in the model. For the range of measured tree heights, the model predicted a substantially narrower range of soil depths (0.5 - 0.9 m) compared with the range of observed soil depths (0.1 - 1.2 m) (Figure 7.4).

Table 7.5 Regression statistics for the simple linear regression of soil depth on individual tree height for QLD case study site.

Summary of fit

R^2	0.23
RMSE	0.21
Observations	36

Analysis of variance

Source of variation	DF	SS	MS	F-ratio	Prob>F
Model	1	0.44	0.44	9.96	0.003
Error	34	1.49	0.04		
Total	35	1.92			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob>t
Intercept	0.08	0.19	0.43	0.67
Height	0.04	0.01	3.16	0.003

Prediction formula:

$$Depth = 0.08 + 0.04 * Height$$

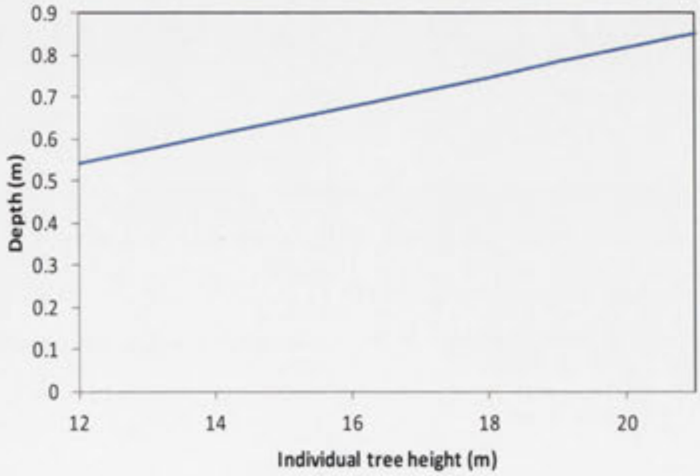


Figure 7.4 Predicted soil depth for the simple linear regression of absolute soil depth on individual tree height at the QLD case study site.

7.6 Applying the tree model to predict fine scale soil depth variation

As discussed in Chapter 2, methods of soil mapping that rely on the direct measurement of soil have a limited capacity to provide information on soil spatial variability at a scale fine enough for the implementation of precision forestry. Results so far have consistently shown that there is a significant relationship between individual tree shape and taper in the butt swell section of the stem and soil depth. The relationship was established for *P. radiata* across several study sites in southern Australia that are widely disparate in terms of their climate, soil and site conditions. The work presented in this chapter demonstrates that the relationship is not only general across different geographical regions, but extends to another *Pinus* species.

In this section, the model developed for the hybrid subtropical pine, *Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis*, is applied to mapping fine scale soil depth variation across the study site. The performance of the stem shape and taper model was assessed by comparison with the conventional method of soil mapping. The stem shape and taper model was also compared with a model based on individual tree height in each section.

7.6.1 Methods

All maps were produced in Geostatistical Analyst, ArcGIS (version 9). Ordinary kriging was used for spatial extension of soil data points. Kriging is a method of spatial interpolation commonly used for mapping soil properties (Chapter 2, Section 2.4.3). Ordinary kriging assumes the absence of underlying trends in the data and uses the spatially correlated (spatially autocorrelated or dependent) component of the spatial variation in the data for local estimation of unknown points. Spatial autocorrelation refers to the assumption that points closer together are more similar to each other than those further apart. Ordinary kriging uses local estimation or only a sample of neighbouring points to estimate values at unknown points. ArcGIS default model inputs were used to generate the semivariograms for the prediction maps (Appendix 4). A spherical model with no anisotropy was used and a smoothing factor of 0.5 was applied to all maps.

Four main maps were generated for this study using ordinary kriging. The total number of sample points where soil depth was measured was used to create a "Base" map, which represents the best soil map available for the soil observations and assumptions implicit in ordinary kriging. The second map represents the conventional soil mapping method ("Conventional" map). The third map represents the tree-based approach created using model predictions of soil depth and the fourth map represents spatial variation of soil depth based on the individual tree height model. Predicted depths at known sample points in the Model maps and Conventional map were contrasted with the Base map both visually and using confusion matrixes (Congalton and Green 2009). Sensitivity analyses were used to examine the effects of sampling error in the creation of the Model map.

Base map and Conventional map These maps were both generated by interpolating from soil observations alone. The Base map was created by interpolation of the full set of 37 soil observations across the site. This map represents the best estimation of spatial variation in soil depth across the site available for the given set of soil observations and assumptions implicit in ordinary kriging, as described above.

In reality, it is not often practical to sample soil at such high intensities. The conventional map was created using a sub-sample of the total number of 37 soil observations. A sub-sample of 10 soil observations was deemed representative of a reasonable sampling effort across the 200 ha study site given the practical constraints of soil measurement, as well as being comparable in effort to the creation of the Model map described below.

Model map The final form of the model for predicting absolute soil depth (Section 7.5) was calibrated using a sub-sample of the total number of co-located tree and soil observations across the study site. A sub-sample of 10 co-located tree and soil observations out of the full dataset of 37 observations was considered the minimal number of sample points required for reasonable model calibration. Smaller sizes were found to result in frequent non-significant parameter estimates. It was ensured that the selected points were well distributed across the approximately 200 ha study area. The calibrated model was used to predict soil depth at each of the 27 sample points not used in the calibration of the model. As these points were not used for model calibration, they provide an independent and unbiased test of model performance.

The model calibrated by the sub-sample of 10 points, along with the predicted depths of all 37 sample points, was used to generate a third map of soil depth variation, referred to as the Model map. A sensitivity analysis was performed to examine the effects of sampling error in the calibration of the model and creation of the map. A series of three soil depth maps were generated using the model calibrated with different sub-samples of 10 soil observations.

Given that the collection of soil depth data for calibration of the model is a major contributor to the cost of the exercise, it was also considered useful to investigate whether the mapped variation in stem shape or taper reflected the mapped variation in soil depth. To illustrate the pattern in stem shape and taper variation across the study site, maps of shape (b), taper (k) and reciprocal taper ($1/k$) using all 37 sample plots and an additional 18 plots, where only tree measurements had been taken, were derived using ordinary kriging and visually compared with the Base map.

Height Model map For comparison with the stem shape and taper model, a map of soil depth variation was produced using the individual tree height model. The individual tree height model was calibrated using a sub-sample of 10 points following the same methods as outlined above for the stem shape and taper model. Two maps were produced: a map of soil depth variation from predictions of tree height, and a map showing the variation of individual tree height across the study site. The height model map was compared with the model predictions of the base map using a confusion matrix.

7.6.2 Results

Base map The Base map indicates that regions of deeper soils are located in the east and through the middle of the study area, with regions of shallower soils located in the north and south-west (Figure 7.5). Shallow soils are mostly in the range of < 0.4 to 0.65 m (5 classes) in depth, while deep soils range from 0.65 to 0.95 m (6 classes).

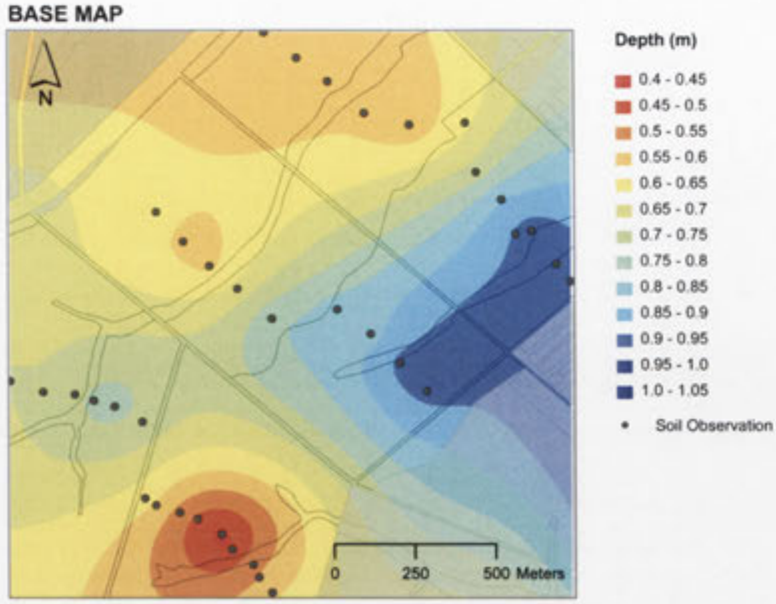
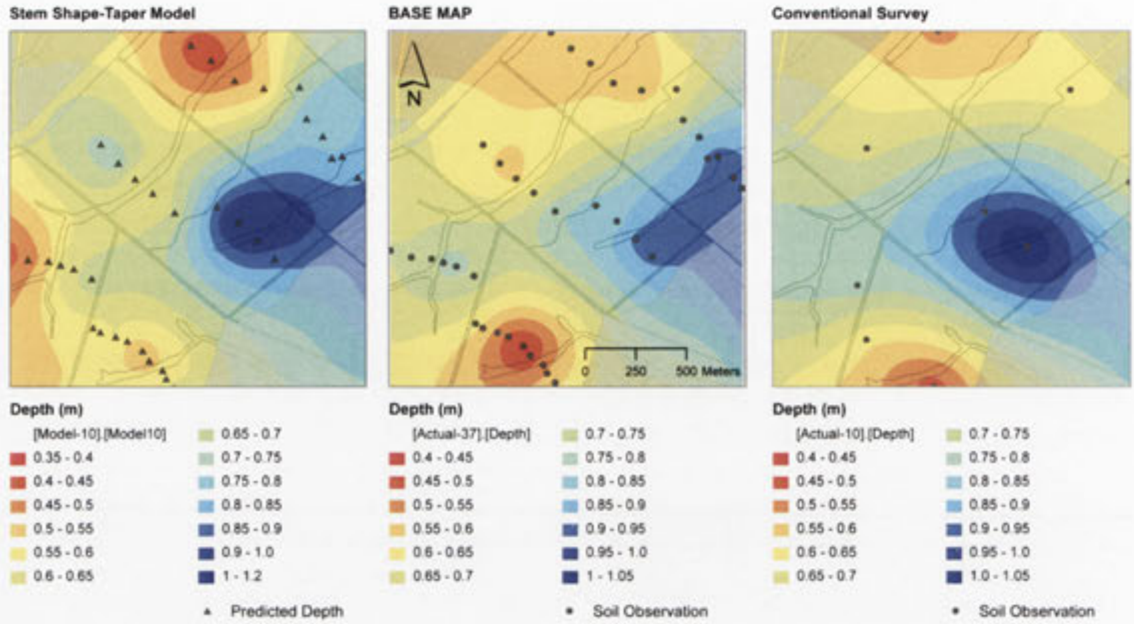


Figure 7.5 The best estimate of spatial variation in soil depth based on detailed soil sampling across the QLD case study site.

Qualitative comparison of the soil mapping approaches The Model map and the Conventional Map were compared with the Base map (Figure 7.6a). In these maps, the total range of predicted soil depth from < 0.4 m to > 1.0 m is divided into a series of 0.05 m classes, showing the differing extents to which each mapping approach has captured the fine scale spatial variation in soil depth across the study area. To facilitate visual comparison, a second version of the three maps was also created (Figure 7.6b). In these maps, the number of depth classes in the original map have been reclassified and reduced from 13 to 5 classes. Both these figures will be referred to in the following description of results.

a)



b)

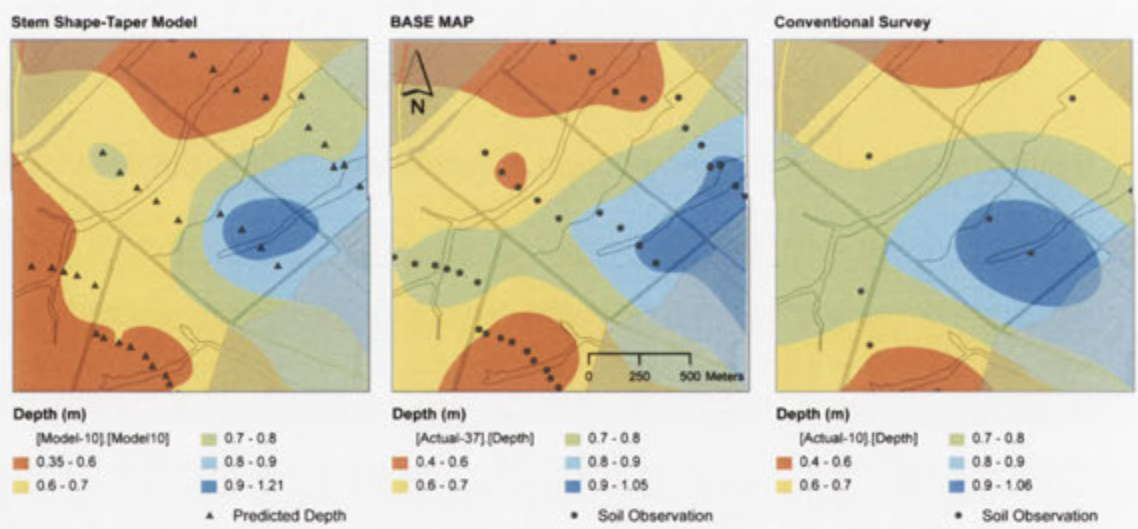


Figure 7.6 Maps of soil depth variation generated using the calibrated model and the conventional method of soil mapping. Figure a) above shows soil depth classified into 13 detailed depth classes and Figure b) below shows soil depth reclassified into 5 broader depth classes.

The regions of shallow and deep soils may be more clearly distinguished in Figure 7.6b. Similar to the Base map, the Model map created using the calibrated model (Table 7.6) indicates that deeper soils are located in the east while shallower soils are located in northern and south-western sites of the study area. By comparison, the Conventional map shows a broad band of deeper soil extending through the centre of the study area, with shallower soils located in northern and southern sites. The Model map better reflects the Base map in some sites, while the Conventional map performs better at others. The Model map more accurately represents the expected areas of shallow and deep soils observed in the in the north (Marker A) and in the north-east (Marker B) respectively, while the Conventional map better represents the expected area of shallow soil in the south (Marker C). The Conventional map indicates that deeper soils extend through the centre of the study area (Marker D). The Base map likewise suggests that deeper soils cross through this region, but not to the same spatial extent.

Differences in finer scale variations in depth may be more clearly observed in the original maps (Figure 7.6a). Both the Model map and Conventional map predict a greater range of depth classes (8 classes) in deeper areas than in shallower areas, than suggested in the Base map (5 classes). Deepest soils in both the Model map and Conventional map are greater than 1 m, while deepest soils in the Base map range from 0.9 - 0.95 m. Likewise, minimum depths are less than predicted in the Base map for the Model map and to a lesser extent, the Conventional map. Shallowest soils in the Model map are less than 0.45 m, while shallowest soils in the Base and Conventional map range from 0.45 - 0.5 m.

Table 7.6 Multiple regression statistics for the model of stem shape and taper calibrated at the QLD case study site.

Summary of fit

R^2	0.68
Root mean square error	0.14
Observations	10

Analysis of variance

Source of variation	DF	SS	MS	F-ratio	Prob > F
Model	3	0.23	0.08	4.3	0.06
Error	6	0.11	0.02		
Total	9	0.34			

Parameter estimates

Coefficient	β	SE β	t-ratio	Prob>|t|
Intercept	-93.85	30	-3.13	0.02
b	0.23	0.09	2.59	0.04
k	32.85	10.59	3.1	0.02
1/k	66.51	20.87	3.19	0.02

Sensitivity analysis: sample selection for model calibration The effect of sampling error in the calibration of the model and creation of the map appears to have minimal influence, but some sites in the study area were more consistently represented than others (Figure 7.7). The first and second sample maps were more similar to the Model map, than the third sample map. The shallower sites in the north (Marker A), west (Marker B), south (Marker C) and the broad expanse of deeper soils on the eastern side of the study area, were reasonably consistent with the Model map for the first two samples. In contrast to the Model map and first two samples, the third sample map (Figure 7.7, Sample 3) indicates that soils are deeper through the middle of the compartment, and shallower in the north.

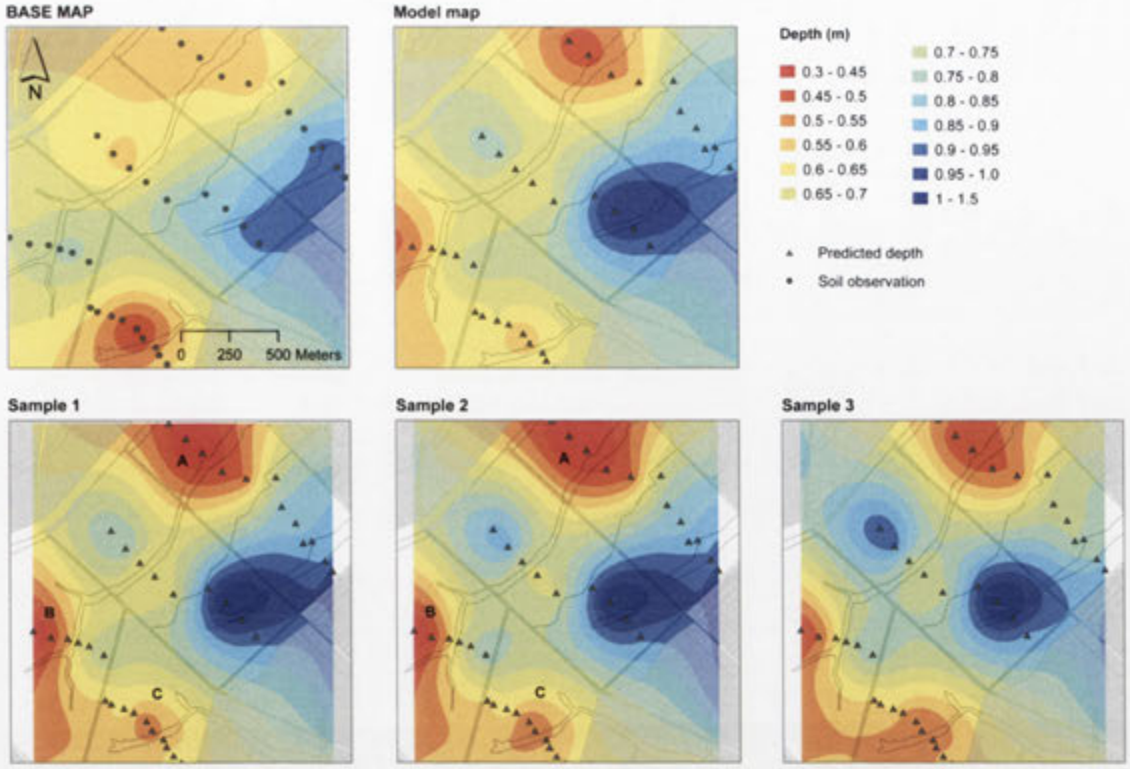


Figure 7.7 Comparison of maps generated from models calibrated with different samples of soil data. The Model map was generated using the calibrated model. The series of three maps below (Samples 1 – 3) show maps of soil depth generated using the model calibrated with three different sets of soil depth observations.

Quantitative comparison of the soil mapping approaches Confusion matrixes were used to compare depth predictions of the model map and conventional map with those of the Base map at each of the 27 sample points excluded from model calibration and spatial interpolation (Figure 7.8). Based on this analysis, the model predicted soil depth with an accuracy equivalent to that of the conventional method. For both mapping methods, depth predictions were correct in relation to the Base map to within 2 classes (10 cm) for just over 65 % of sample points or to within 3 classes (15 cm) for about 85 % of sample points. Closer examination of standard errors for the shape and taper values of the predictions inaccurate by more than 4 depth classes showed nothing unusual and their errors were well within the expected range. Overall, predictions were never inaccurate in relation to the Base map by more than 5 depth classes or 30 cm at any sample point for either mapping method.

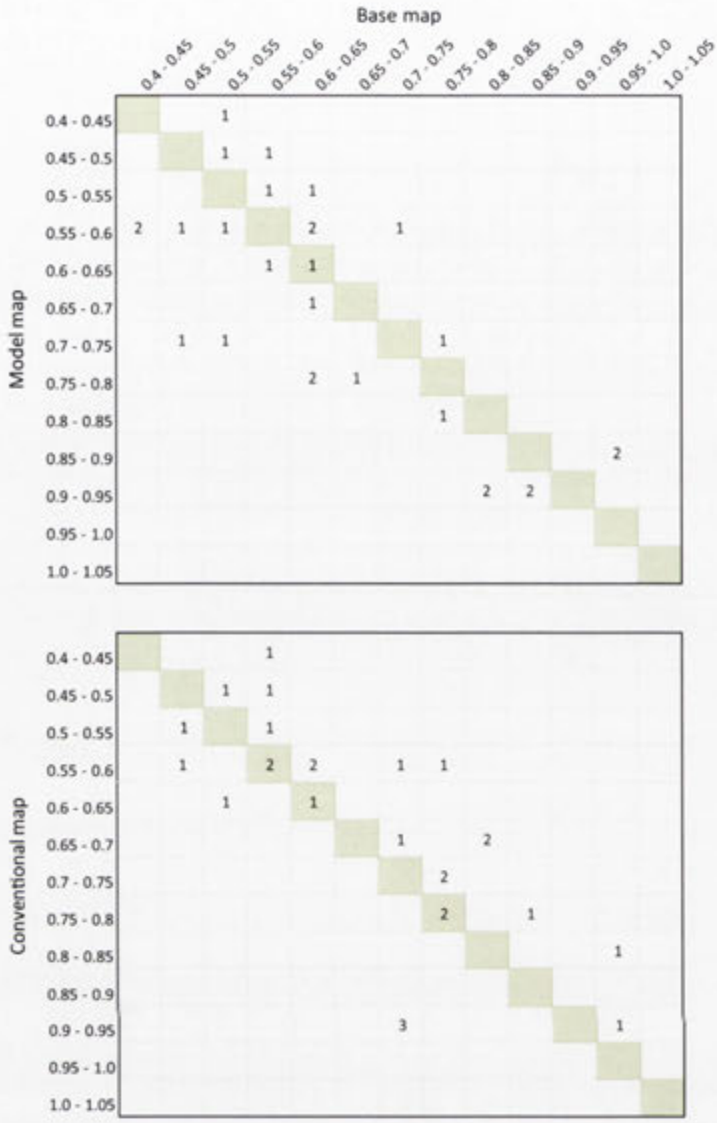


Figure 7.8 Confusion matrixes comparing the accuracy of maps generated using a) model predictions and b) conventional soil sampling with the base map. The shaded cells indicate a match in depth class between mapping methods.

Spatial variation in stem shape and taper in the butt swell Given that the model (Table 7.6) has positive coefficient estimates for shape (*b*), taper (*k*) and its reciprocal (*1/k*), it can be expected that larger values of each variable would be associated with deeper soil. Based on this assumption, both maps of *1/k* and *b* correctly indicate that the deepest soils would be in the central eastern sites, while the shallower soils would be in the north and south western sites (Figure 7.9). The mapped variation in *k* indicates the converse trend, with deepest soils predicted in the north and south western sites and shallower soils in the eastern sites.

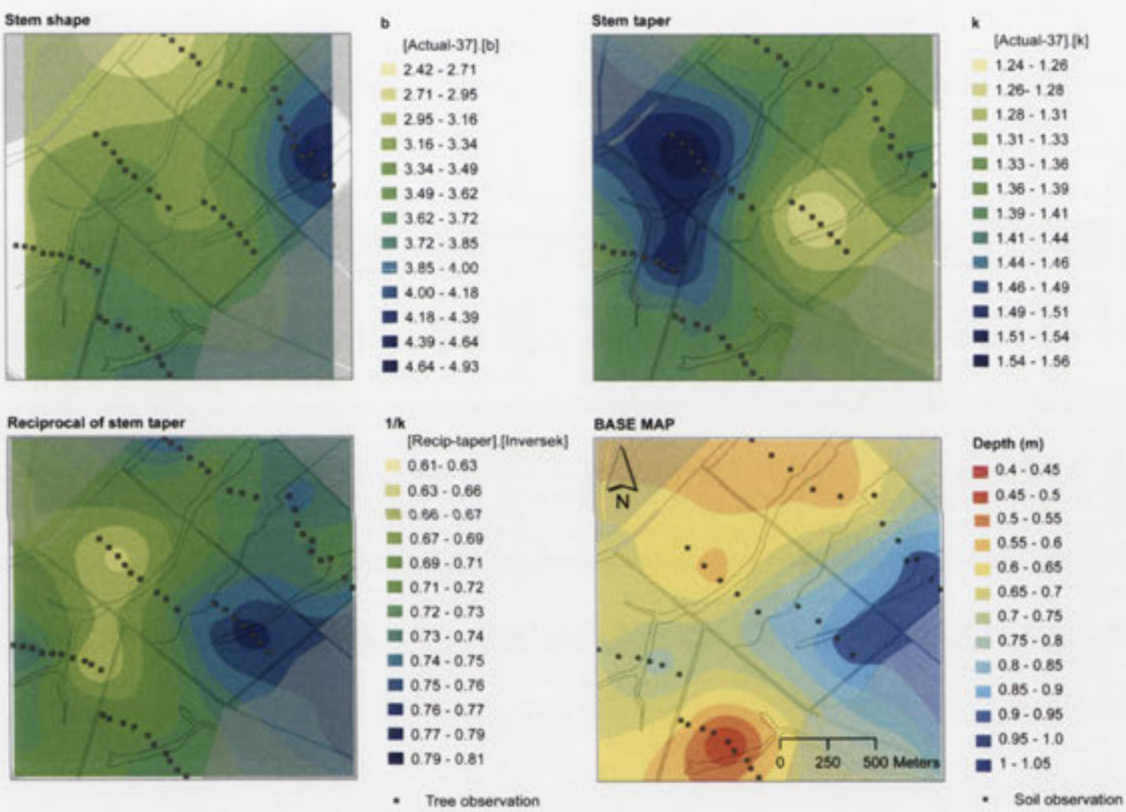


Figure 7.9 The spatial variation of stem shape, taper and reciprocal of taper across the QLD case study site.

Comparison of stem shape and taper with individual tree height The height model predicted zones of relatively shallow soils in the west and relatively deep soils in the east of the study area. These broadly corresponded to the depth variation represented in the Base map (Figure 7.10). Predictions of the height model were correct in relation to the Base map in 18 % of cases (Figure 7.11). The tree height model did not explain as much of the variation as the shape and taper model or the conventional soil survey method. Predicted soil depth values ranged from 0.5 - 0.8 m.

Spatial variation of individual tree height across the study site broadly reflected regions of shallower and deeper soils as depicted in the Base map (Figure 7.12). Zones of shorter and taller trees corresponded well with the zones of shallower and deeper soils shown in the Height model map. The attempt to quantify this correlation using linear regression did not capture as much of the variation in soil depth as the stem shape and taper model ($R^2 < 0.37$ shape and taper model vs. $R^2 < 0.23$ tree height model).

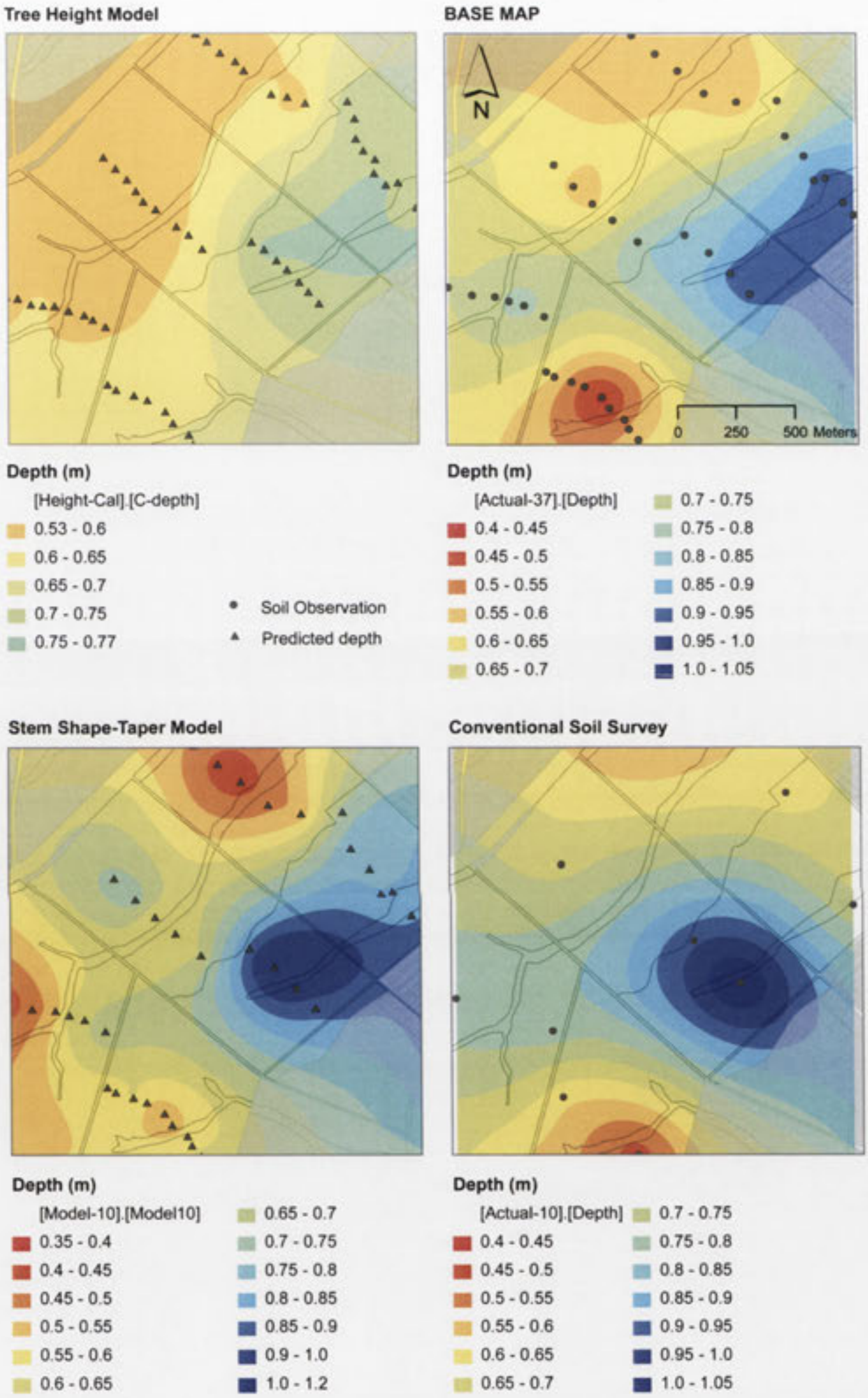


Figure 7.10 Comparison of maps based on model predictions and maps based on conventional soil survey.

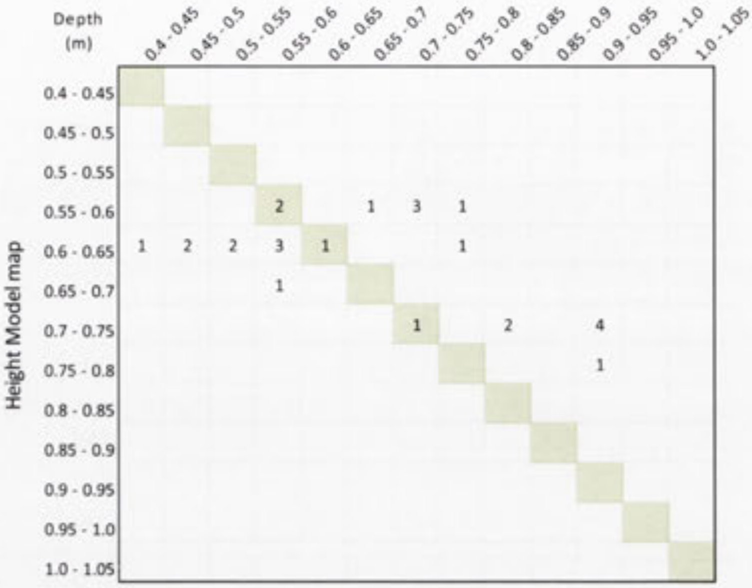


Figure 7.11 Confusion matrix comparing the accuracy of the Height Model map with the Base map.

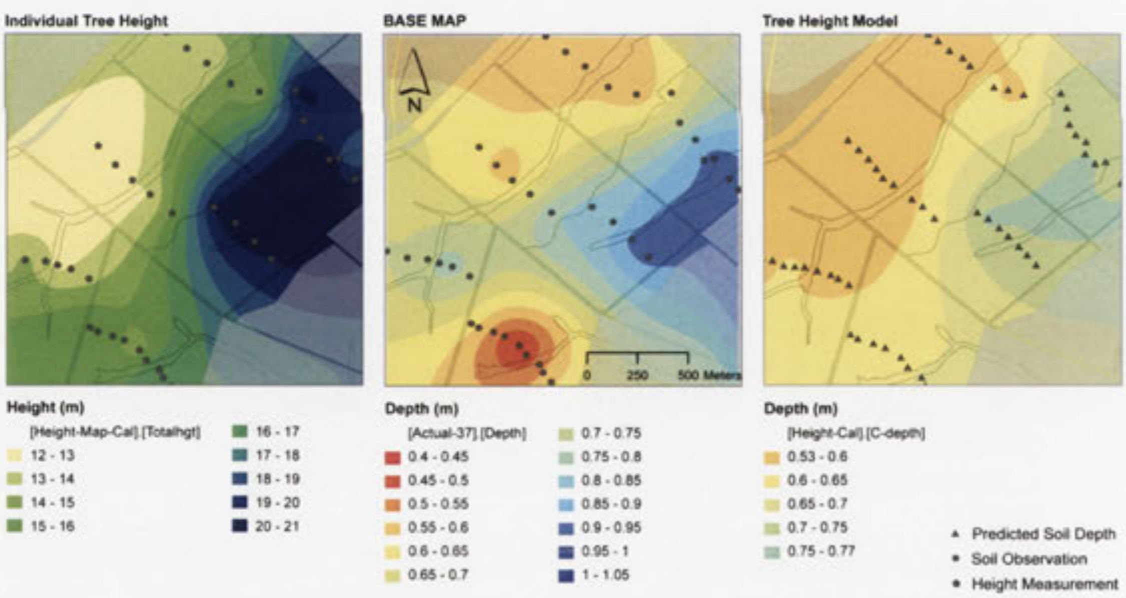


Figure 7.12 The spatial variation of individual tree height across the QLD study site compared with soil depth variation predicted by the base map and the individual tree height model.

7.7 Discussion

Stem shape and taper were both significant predictors of soil depth for the hybrid subtropical pine, *Pinus elliottii* var. *elliottii* x *Pinus caribaea* var. *hondurensis* in the Queensland case study site. At this site, a weighted combination of shape and both the direct and reciprocal expressions of taper, to provide a curvilinear relation, were found to provide the best fit to the data. The curvilinear relationship found for this region and species provided a contrast to the linear correlations previously found for *P. radiata* in the South Australian and New South Wales case study sites.

These apparent differences may be due to the interactions between effective soil depth and other soil properties, especially texture. The interaction between soil depth and texture properties are known to be complex as they influence other major soil determinants of growth, such as moisture storage, internal drainage and aeration (Jackson 1962). Changes in the direction and form of the relationship between effective soil depth and tree growth parameters in response to differences in soil physical characteristics, such as texture, clay mineral content, particle size distribution and bulk density, have been noted by several authors. For instance, Pegg (1967) showed that the site index of *P. elliottii* was positively correlated with increasing soil depth in soils with clay loam textures, but negatively correlated in soils with loamy textures; while Ryan (1986) found that the relationship between the basal area of *P. radiata* and soil depth was linear on siltstone parent material, but non-linear (exponential) on conglomerate.

It was observed that inflection points for the Queensland absolute depth model occurred at 0.5 m, the same depth at which data points converged in the preceding model for *P. radiata* in the South Australian study site. Based on these observations and as alluded to in previous discussion (Chapter 6, Section 6.4), this may have a physiological basis. It is hypothesised that the structure of the stem base might change in relation to differences in the dominant factor/s required for tree survival at different critical or threshold depths. For example, mechanical stability and support might be the dominant factor influencing tree survival in shallow soils which influences the growth response in the base of the tree stem, changing shape and taper. In deeper soils, the dominant factor influencing tree survival and the development of shape and taper in the base might be the availability of nutrients and water; whilst in yet deeper soils that are beyond the reach of tree feeder roots, soil resources would not be expected to be influential. Hence, different factors may dominate at different zones in the soil profile, modifying shape and taper in the base of the tree accordingly. The change in the relationship observed at 0.5 m in Queensland and South Australian models raises the notion that a hypothetical threshold depth or zone may occur at about 0.5 m for the regions and *Pinus* species sampled. If this is the case and the dominant processes required for tree survival change at around 0.5 m, further study to understand this association on a physiological basis, might focus on exploring this zone of change by dividing trees into deep or shallow depth classes at different depth thresholds.

Results indicate that the application of the model may be divided into two aspects. The first is the use of the relationship described in the model to map spatial variation in relative soil depth and the second is the calibration of the model to predict and map spatial variation in absolute soil depth. As shown in the maps of tree shape, taper and reciprocal taper (Figure 3.31), the spatial variation in basal tree shape parameters alone provides a reasonable estimation of the relative variation in soil depth. Tree shape information is not only relatively cheap to collect using traditional methods of field survey, but mechanical harvesting systems routinely collect detailed stem shape data across the estate during harvesting in most major Australian plantations. These systems may need modification to assess the base of the stem, but potentially offers the ability to systematically map soil depth variation across the plantation estate at minimal or no additional cost. Furthermore, new technologies such as ground-based lidar have recently shown much promise for quick and accurate retrieval of tree stem parameters in early trials (Strahler, Jupp et al. 2008). Based on this, the ability to map soils using tree shape information has significant potential for easy implementation into current forest management systems. Understanding the relative pattern of depth variation across the plantation estate has a range of benefits for improving forest operations and activities, such as minimising the major environmental impacts of soil compaction and erosion associated with forest road construction, and reducing the cost of silvicultural activities, such as thinning, pruning, and fertilisation, by applying these on a site-specific basis.

The second aspect of model application relates to the calibration of the model to enable accurate prediction of absolute soil depth at the plot or individual-tree level and the spatial interpolation of that point data to create maps of absolute soil depth variation. Examination of confusion matrixes indicate that the calibrated model is predicting soil depth with an accuracy equivalent to the conventional method of mapping based on interpolation of soil observations alone. Improving the performance of the model would involve increasing the number of co-located soil and tree observations used in its calibration. On the other hand, minimising the cost of the exercise depends on minimising the number of soil observations used.

As the spatial variation of tree shape and taper across the site were shown to reflect soil depth variation, increasing the number of tree measurements used for spatial interpolation rather than the number of points used for calibration may offer a more cost effective solution for improving map accuracy in future work. This would rely on there being a sufficiently strong relationship between the shape and taper of the butt swell and soil depth to add more "signal" than "noise" to the map. Results suggest that for the range of soil depths explored, maps based on soil observations alone were as good as maps based on the same number of soil observations augmented by depth predictions from additional trees. It follows that there must be some optimum number (and distribution) of soil depth observations required to calibrate a soil depth model for subsequent use in predicting soil depth variation across an area. The weaker the relationship between soil depth and the independent variables used to predict soil depth, in this case shape and taper of the butt swell, the more effort would need to be spent to calibrate the relationship (i.e. more soil depth measurements would be required).

Comparison of the model map with the base map suggest that the model in its current form may be missing the terms required to adequately account for the curvilinear trend observed at this site. As regression methods tend to predict the mean dependent variable for any given, even extreme, independent variable, models typically predict a smaller range of variability than the range of data from which they were developed (Ramsey and Schafer 2002). Contrary to this expectation, mapping of the predicted soil depth showed a greater range of depths than suggested in the Base map (Figure 3.28a). One possible explanation is that the model in its current form is not adequately incorporating the curvilinear effect apparent at this site, and as such is being extrapolated beyond its useful range of independent variables. Examination of the sample data collected indicated that higher values of shape and taper and lower values of shape and taper were associated together; but only in a few instances were high and low values of shape and taper associated together (Appendix 3). Thus, there may be some interactions between b and k in these under-explored regions which may result in a curvilinear response. Given that sampling was unable to determine a significant pattern in these regions, the application of the model as developed might be over-estimating the depth or shallowness in areas of the study site where these unusual combinations of b and k occur. A higher density of observations is required in these areas of the study site to identify missing terms or interactions in the model and also to reduce the distance between sample points, to improve the accuracy of spatial interpolation.

Individual tree height was consistently shown to be a significant predictor of soil depth throughout this study. In some cases, height was a better predictor of soil depth properties than stem shape and taper, such as in SA for predicting depth class. However, there appeared to be no obvious advantage in using a model based on individual tree height than one based on stem shape and taper when applied to mapping soil depth variation. The map produced using the stem shape and taper model better represented the finer scale variability of soil depth across a broader range of depths, near equivalent to the range of observed values, than the tree height model. In terms of which model better captured spatial variation in soil depth, the model based on stem shape and taper appeared to perform at least as well as, if not better, than the model based on individual tree height.

The assumption underlying the use of kriging as a method of spatial interpolation is that of "stationarity"; i.e. that there is no underlying spatial trend surface affecting the variation in soil depth. As hydrological and hill-slope processes produce predictable variations in soil depth in undulating landscapes, which are typical of many forested areas, further work might explore the use of non-stationary models which enables the integration of other key environmental data such as terrain variables, to improve the accuracy of the interpolation e.g. Minasny, McBratney et al. (2008). Since this requires data that was not made available at the time and a considerable amount of work outside the scope of the current study, the use of non-stationary models would be a topic of investigation recommended for future work. The availability of digital environmental layers would further provide a useful guide for determining optimal placement of sample points.

7.8 Summary and conclusions

The results of this chapter demonstrate that the general relationship between stem shape, taper and soil depth established for *P. radiata* sites in southern Australia is also applicable to a subtropical region in southeast Queensland and to a different *Pinus* species. The fact that the model can be applied to another species provides some level of confidence that the relationship could be further extrapolated to a range of other important plantation species with similar physiology and rooting habit.

Similar to the models for *P. radiata*, differences between slope parameters for each region in the regression model suggest local calibration is required for the region and plantation species to which it is applied. On a physiological basis, the change in the relationship between stem shape, taper and absolute soil depth at a depth of around 0.5 m predicted by both the Queensland model and by preceding models developed in SA and NSW, suggest that the nature of the relationship may be influenced by changes in the availability of soil resources at different zones or critical depths in the soil profile.

The calibrated stem shape and taper model was successfully applied to mapping both relative and absolute spatial variation in soil depth across the plantation site. In its current form and stage of development, the model is performing at a level of accuracy equivalent to that of the conventional method. This result is promising and the ready availability of detailed stem shape data from other forest operations and processes, offers the potential for further improvements to the model to be made at minimal cost. It may also be the case that the more widespread adoption of high-resolution remote sensing, such as lidar, generates such information at even lower cost. These opportunities are discussed further in the next chapter.

Chapter 8: Synthesis of results and concluding discussion

8.1 Introduction

This chapter reviews the key aims and hypotheses of the thesis, discusses them in relation to the overall results and provides a general discussion of the implications of the research.

8.1.1 Research aims and questions

The research reported in this thesis investigated whether measurements of tree shape and taper in the basal 2 m of the stem may be useful predictors of fine scale variation in soil properties important to forest management, particularly effective soil depth. To investigate this topic, this study addressed the following research questions in the context of Australian *Pinus* plantations:

1. Is there a relationship between stem shape and taper in the butt swell and soil depth for *P. radiata*?
2. Is the relationship general and consistent under a range of site conditions and soil types for *P. radiata*?
3. Can absolute soil depth at the individual tree scale be estimated from a calibrated model for *P. radiata*?
4. Is soil depth a simple index for more complex soil resources and can these other relationships with stem shape and taper be quantified?
5. Is the relationship with soil depth generalisable to other *Pinus* species?

6. How does mapping a tree-based model for mapping soil depth variation compare to the conventional method of extrapolation from soil observations alone?

As described in Chapter 3, plantation *Pinus* species in southern and eastern Australia were used to investigate the relationship between tree shape and taper in the base of the tree and soil properties. Work was conducted as a progressive sequence of case studies, moving from the more simple research objectives to the more complex. This sequence of studies and their outcomes are summarised in the following section.

8.2 Summary of results in relation to thesis aims

Research to address thesis objectives and hypotheses was divided into a sequence of four studies. The first three studies were in *P. radiata* plantations of temperate southern Australia and the fourth in sub-tropical *P. elliottii x P. caribaea* plantations. The main aims of each study and their outcomes are summarised in Table 8.1.

Research Question 1: Is there a relationship between stem shape and taper in the butt swell section and soil depth for *P. radiata*?

A significant relationship was established between stem shape and taper in the butt swell section and soil depth for *P. radiata* at all case study sites visited. The relationship was first established between soil depth and stem shape and taper using soil depth class as a crude but easily assessed proxy for soil depth (Chapter 4). The relationship with actual soil depth was established and further explored in later stages of work (Chapters 4-6). A regional term was included in all models to account for large scale variations in site, such as climate, between regions.

Research Question 2: Is the relationship general and consistent across a range of site and soil conditions for *P. radiata*?

Lower tapers and higher stem shapes were associated with deeper soils at all the four study regions that included *P. radiata*. Significant parameters in the model were stem shape, taper and region. The model was improved with the incremental addition of data as work progressed. The strength and coefficients of the significant relationships identified varied between the regions and were occasionally influenced by significant interactions between shape, taper and region parameters. While the linear form of the model is consistent between regions, calibration is required to estimate the regionally-specific parameter coefficients.

Research Question 3: Can absolute soil depth be estimated from a calibrated model for *P. radiata* at the individual tree level?

The calibrated stem shape and taper model can be used to predict soil depth at the level of the individual tree. Absolute soil depth was significantly correlated with stem shape and taper in a multiple linear regression at all study sites where depth measurements were available.

Research Question 4: Is there a relationship between stem shape and taper in the butt swell and other soil parameters?

No strongly significant ($p < 0.05$) simple linear relationships could be established with other more complex soil variables; although some weak correlations with soil nutrients were identified. This result was not unexpected given the small sample size. A combination of soil properties from the A horizon were also found to be significant predictors of stem shape and taper. However, the model was overparameterised (Chapter 6). Results indicate that there is a broad relationship but more data would be required to quantify relationships with individual soil variables.

Research Question 5: Is the relationship generalisable to other species?

The relationship was successfully established for a subtropical species of pine (Chapter 7), which suggests the potential to extend the model to a range of other important plantation species. Unlike the linear relationship established for *P. radiata*, the relationship between stem shape and taper and soil depth was found to be curvilinear for subtropical pine in the QLD case study site (Figure 7.3). As the model was only developed for a single region, more data for the same species of subtropical pine from a different region would be required to clarify whether this result was mostly an artefact of small sample size or due to a regional or species effect.

Table 8.1 Summary of main thesis outcomes

Research Question	Task	Site	Model	Principal Results
1. Is there a relationship between stem shape and taper in the butt swell section and soil depth for *P. radiata*?	Establish a relationship between tree shape parameters and soil depth class in ACT and TAS.	Shallow, clayey, nutrient limited soils and low rainfall in ACT Deep, fertile soils and high rainfall in TAS	Preliminary soil depth class model	A relationship between stem shape and taper in the butt swell and soil depth class was identified and described in a preliminary model.
2. Is the relationship general and consistent across a range of site conditions and soil types for *P. radiata*?	Expand data collection to SA to confirm relationship identified in previous stage of work.	Deep, sandy, nutrient limited soils and high rainfall.	Cross-regional soil depth class model	The relationship between stem shape and taper in the butt swell and soil depth was confirmed. The preliminary model was improved by the addition of new data and a third study region.
3. Can absolute soil depth at the individual tree scale be estimated from a calibrated model for *P. radiata*?	Investigate potential for predicting absolute soil depth from stem shape and taper using SA data.	Deep, sandy, nutrient limited soils and high rainfall	Preliminary single-region absolute soil depth model	A preliminary but statistically significant model for prediction of absolute depth was developed using the SA data.

	Refine soil depth class and absolute soil depth models developed in previous regions with the addition of data from NSW.	Deep, nutrient-rich soils at Green Hills; shallow shale soils in Carabost; high rainfall at both sites	Refined cross-regional soil depth class model Refined cross-regional absolute soil depth model	Addition of new data from a fourth region improved estimation of coefficients for the depth class model. Development of a statistically significant model for prediction of absolute depth in both SA and NSW.
4. Is there a relationship between stem shape and taper in the butt swell and other soil parameters?	Explore relationship with other soil properties in NSW	Deep, nutrient-rich soils at Green Hills; shallow shale soils in Carabost; high rainfall at both sites	Preliminary single-region model for prediction of stem shape and taper from soil properties	Neither shape nor taper were strong predictors of any individual soil property. In contrast, a range of soil properties were significant predictors of shape and taper, leading to the development of a preliminary model for prediction of shape and taper from a suite of key soil properties.
5. Is the relationship with soil depth generalisable to other *Pinus* species?	Establish application of absolute depth model to sub-tropical species and soils in QLD.	Deep sandy soils prone to water logging in some areas, high rainfall	Absolute depth model	A statistically significant relationship was established between shape and taper in the butt swell and absolute depth for a sub-tropical species and soils. In contrast to the preceding studies (1 - 3), the relationship was curvilinear.
6. How does mapping soil depth variation from the absolute soil depth model compare to the conventional method of soil mapping?	Assess practical utility of absolute soil depth model for mapping spatial variation in soil depth at the QLD site.	Deep sandy soils prone to water logging in some areas; high rainfall	Calibrated absolute depth model	The map based on the absolute depth model produced a map of soil depth variation with an accuracy equivalent to the map based on conventional soil sampling.

Research Question 6: How does a tree-based model for mapping soil depth variation compare to the conventional method of extrapolation from soil observations alone?

A quantitative comparison of the conventional and tree-based approach to soil mapping (Figure 3.30) indicated that the stem shape and taper model in its current form is performing at a level of accuracy equivalent to the conventional soil mapping method. However, regions of deeper and shallower soils were more accurately depicted in the map based on model predictions (Figure 3.28). This result is encouraging as improvements to the model can potentially be made at minimal cost. These opportunities are discussed in the following sections.

8.3 Implications of results and further development

8.3.1 Implications for understanding the physiological development of stem shape and taper in the butt swell

Results consistently indicated that tall trees with high stem shapes and low tapers in the butt swell section were associated with deeper soils (Figure 8.1). The physiological development of the butt swell section is not well understood (Chapter 2). Stem shape and taper in this section of the stem have been attributed to a range of factors such as the weight of the stem and crown, effective soil depth and texture of the rooting medium, type of root development and the conditions of exposure. The results of this thesis suggest that stem shape and taper in the butt swell section may be driven primarily by the volume of below-ground resources and furthermore, may be controlled by a series of thresholds that change with the depth of the soil profile. As the relationship between stem shape and taper with soil depth was not always linear and changed with soil depth at some sites (e.g. at SA and QLD sites), it could be speculated that different factors influence stem shape development at different depths. For example, basal stem shape and taper might be a response to the tree's dominant need for mechanical support and stability in shallow soils; whilst those properties that influence feeding, such as soil nutrients and water, might dominate stem shape and taper response in deeper soils. More research peripheral to the aims of this thesis would be required to further understand the development of stem shape and taper in the butt swell section and how it may vary with soil depth.

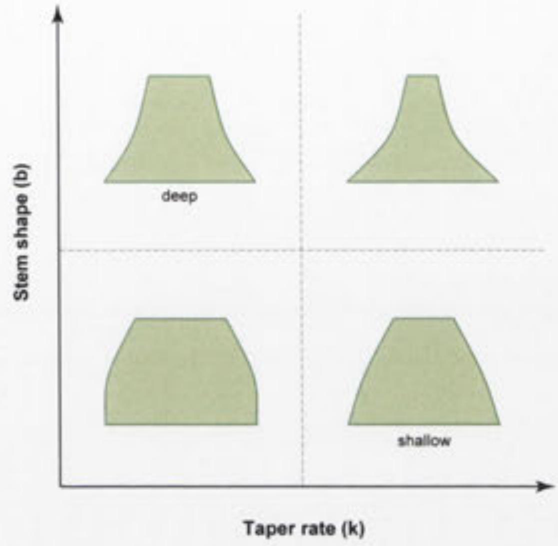


Figure 8.1 Schematic representation of the generalised pattern of the relationship between soil depth and stem shape and taper in the butt swell.

8.3.2 Implications for improving modelling and mapping of fine scale soil depth variation

The research reported in this thesis is the first time that a relationship between soil resources and shape and taper in the butt swell has been quantified in a model. These results have a number of implications for soil mapping and forest management, improving taper models and volume estimations and more accurate carbon accounting.

Previous chapters of this thesis demonstrated how fine scale spatial variation in soil depth can be modelled and mapped (i.e. predicted and interpolated from predictions, respectively) using simple measurements of stem shape and taper in the butt swell section of the stem. The relationship between stem shape and taper in the butt swell section and soil depth was found to be both consistent and general across a range of site and soil conditions in southern Australia, and across the two plantation taxa sampled. This finding provided a strong basis on which to explore the development and potential implementation of a practical, low-cost method for modelling and mapping fine scale spatial variation in soil depth properties.

8.4 Implementation, limitations, and further development of a tree-based approach to soil mapping

Some aspects of this work could potentially be implemented within current forest measurement and management systems; others would require further development. Implementation, limitations and further development of a tree-based approach to mapping soil depth may be divided into two main aspects: the refinement of models for prediction of soil depth at the individual tree level; and the improvement of spatial modelling of soil depth based on model predictions.

8.4.1 Refinement of soil depth models

The soil depth models in their current forms and stages of development are regionally specific, requiring calibration to the region of interest using a number of co-located soil depth and tree shape and taper measurements. Reducing the cost of a tree-based approach to soil mapping would rely on minimising the number of soil measurements needed for model calibration. Due to constraints of time and resources, this current work does not provide a basis for establishing the optimum number and distribution of soil depth observations required to calibrate the model. The amount of effort that would need to be invested in model calibration would depend on the strength of the relationship between soil depth and the tree shape and taper of the butt swell at a given location. Future work to improve model calibration would involve increasing the number and density of samples collected from each study site already visited and including in model development data from other major softwood plantation growing regions in Australia not previously included in this research. For *P. radiata*, this would mean sampling in other regions with substantial plantation estates, such as the Bathurst/Oberon plantation estates in New South Wales and those in Victoria. Model development would be facilitated by sampling sites where the growth of *P. radiata* is limited by soil depth, as well as those where soil depth is not a limiting factor.

Improving models and developing a better understanding of the relationships and interactions between stem shape, taper and other soil properties important to tree growth, would require more detailed soil analysis than was possible in this study. The work conducted at the two New South Wales sites identified several simple linear relationships, such as for available nitrogen, but results were not consistent between the two plantation sites sampled. Clarifying the nature of the relationship would enable optimisation of model performance and offer the potential to predict a range of other soil properties.

The Queensland case study demonstrated that the relationship between stem shape, taper and soil depth established for *P. radiata* could also be extended to a species of subtropical pine. This has introduced the possibility of developing a more general model applicable to both temperate and subtropical plantation growing regions in Australia. However, a curvilinear trend in the current model for subtropical pine indicated that different factors and processes dominate at different depths (Chapter 7, Section 7.7). It is speculated that the form of the model proposed in this thesis is incomplete and there may be other influential variables that have not been included. Increasing the number of soil samples and variables and extending work to a range of other subtropical plantation regions, such as those elsewhere in Queensland and northern New South Wales, would be necessary to understand what other factors influence the relationship and to improve the accuracy of model predictions for subtropical *Pinus* taxa.

Given the importance of eucalypts in Australian plantation forestry, it might also be of interest to explore whether such a relationship, as found here for *Pinus* species, can be extended to other genera. Similarly, future work might also explore if the relationship found here for exotic pines applies to the native conifer *Araucaria cunninghammii*, grown in approximately 45 000 ha of plantations in south-east Queensland and northern New South Wales. These plantations have been established on generally more fertile sites than those for exotic pines. Following on from this, it may also be of interest to extend the work to at least some of the large (approximately 1 million ha) eucalypt plantation estate now established primarily in southern Australia and dominated by *Eucalyptus globulus* (BRS 2010).

8.4.2 Improvement of spatial models of soil depth

Improving the accuracy of soil maps is conventionally achieved by increasing the density of soil sample points. Improving the accuracy of soil maps using a tree-based approach could rely on improving the model itself by increasing the number and density of co-located soil and tree measurements used for calibration as discussed in the section above; but in terms of cost, this would only be practical up to a point. Alternatively or in conjunction, increasing the density of tree measurements may substantially improve the accuracy of the spatial interpolation without a proportionate increase in cost. However, this would depend on there being a sufficiently strong relationship between stem shape and taper and soil depth to increase the signal to noise ratio, as discussed in Chapter 7.

An outcome of this work which can be most readily implemented is the ability to obtain relative soil depth information by examining the spatial variation of stem shape and taper in the butt swell section of the stem (Chapter 7). The ability to easily identify and map areas of relatively deep or relatively shallow soils would provide sufficient information to guide decision making for a variety of precision forestry operations, such as tree selection for thinning or pruning activities and application of fertiliser given a limited budget. The extent of variation in soil depth captured by the spatial variation of stem shape and taper will depend on the density of tree observations. As detailed stem shape information is available across plantation compartments, this aspect of the research can be most readily implemented within current management processes.

Systematic collection of tree shape measurements across the plantation estate during mechanical harvesting and thinning operations is now routine across most plantation growing regions in Australia, even if relatively little use is currently made of this information for forest management. It is also the case that this information is relatively cheap to collect through conventional field survey and in addition to this it is likely that new technologies such as terrestrial lidar will further reduce the cost. Understanding the larger scale pattern of stem shape and taper variation across the plantation compartment also offers the opportunity to explore more advanced methods of spatial interpolation, such as universal kriging which uses global rather than local estimation of unknown points, or co-kriging, which enables better estimation of mapped values by using more cheaply and intensely sampled secondary variables. The use of more powerful methods of spatial interpolation can be expected to lead to improvements in map resolution and accuracy.

The outcomes of this research may provide a useful basis on which to improve forest biomass or above-ground carbon determination. As discussed in Chapter 3, height-driven taper functions typically perform poorly in the butt swell section of the stem. Findings suggest that, unlike the upper stem sections, the development of shape and taper in the base of the stem may be predominantly driven by soil resources. The base of the stem contains a substantial proportion of the overall stem biomass. For this reason, the ability to develop taper functions that perform well in the base of the stem would have significant implications for improving the accuracy of whole tree biomass estimations. This aspect of the research may also have implications for soil carbon modelling. Results suggest that the relationship between stem shape and taper of the butt swell and soil depth may be driven by the interplay of structural support for the tree and the potential for exploitation of minerals and water. Given that coarse roots and fine roots relate to support and feeding respectively, it is hypothesised that shape and taper may also relate to the quantity of course and fine roots, and therefore the quantity of below-ground carbon. Considering the increasing importance of forests for carbon sequestration and the likely interest of policy makers and forest managers in adapting forest management to conserve carbon, a simple and robust means of estimating soil carbon – currently one of the most difficult carbon parameters to assess on a large scale – would be of considerable interest.

8.5 Summary of key conclusions and future research priorities

This thesis has demonstrated that there is a consistent and quantifiable relationship between the stem shape and taper of the butt swell section and soil depth; and that the relationship has practical application for mapping fine scale spatial variation in soil depth for two types of *Pinus* species. With further work, this approach may be extended to other important plantation species. At this stage of development, maps based on soil observations alone (conventional soil survey) were no better than maps created using the same number of soil observations augmented by model predictions of soil depth. Even though no generally applicable model was found, there was a consistent linear relationship between stem shape and taper parameters and soil depth at all sites. Trees with lower tapers and higher shape parameters in the butt swell section were consistently found on deeper sites. Relative change in soil depth across an area may therefore be estimated without model parameterisation. This aspect of the model is general and consistent at each plantation site and may be used to obtain relative soil depth information cheaply and efficiently.

To determine whether the model is useful in practice, more work needs to be undertaken to calibrate the model. The number and distribution of soil observations required will depend on the strength of the relationship between stem shape and taper of the butt swell and soil depth. With further refinements to the model, a tree-based approach to fine-scale soil mapping could show considerable promise for cheaply and efficiently generating the information necessary to support the current shift towards precision management of the Australian plantation forest estate.

This research has provided further insight into the physiological drivers for the development of shape and taper in the butt swell. Results suggested that different interactions and thresholds for nutrients, water or structural support, may dominate the relationship with stem shape and taper in the butt swell at different depths of the soil profile. More work to further understand this relationship will have a range of implications for forest soil mapping, precision forest management and related issues, such as modelling above and below ground forest carbon.

On the basis of the results presented in this thesis, future work to advance related knowledge and extend aspects of the current research may include:

- Improving soil depth models by standardising soil depth measurement across sample sites. One of the key limitations of this work was, as discussed in Chapter 3, that there was no standard specification of soil depth properties used. Further work should therefore involve a standardised approach with characterisation of a broader suite of soil variables, particularly those that characterise soil effective volume in addition to soil depth: e.g. coarse fragments, bulk density and soil texture. The effect of using a combined dataset with different maximum recorded depths on the fit of the model is also an aspect requiring further investigation. The use of non-invasive techniques for quantifying effective soil depth, such as ground penetrating radar, conductance/resistivity and seismic sensors, may also be helpful.

- Improving soil depth models by exploring the extent to which the regional parameter may or may not account for gross differences in site, stand, and management histories.

- Exploring the use of other practical height levels along the stem to define the butt swell section. In this thesis, the butt swell section was defined as the shape and taper in the bottom 2 m of the stem. Further work could examine the sensitivity of findings to this definition. Stem shape and taper of the butt swell at other practical heights, such as the bottom 1.3 meters (i.e. to breast height) of the stem may be most practical or heights greater than 2 m may be possible with the aid of ground-based lidar.

- Examining the time at which the 'signal' or influence of soil depth on the stem shape and taper of the butt swell first becomes evident. Age relationships could be examined through dendrochronological analysis.

- Improving accuracy of spatial analysis by using non-stationary models of spatial interpolation to incorporate co-variates.

- Exploring the potential of lidar for simplifying measurement of stand height in general, as well as of individual tree attributes of height, shape and taper.

- Assessing the utility of currently available data on individual log diameter/length produced by modern harvesting machinery for estimating shape, taper and merchantable height. However, this information would only be useful if logs are routinely tagged with a geo-position.

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Appendix 1 : Hypsometer test

An experiment was conducted to test the accuracy and precision of different hypsometers and methods for measuring height. A Laser Criterion and three different Vertex instruments in both laser and sonic modes were used to measure the vertical distance of a building from ground-level to selected heights along its length. Instruments were tested by three operators.

Results indicated significant differences ($p < 0.05$) between instruments tested (Figure A1.1, Table A1.1). Measured heights have been reported as a percentage of 'true' height (100 %), as measured by height stick. The Criterion Laser hypsometer fitted to a tripod produced the most accurate and precise measurements, with errors of approximately ± 2 % of the true value. The performance of hand-held Vertex hypsometers was more highly variable. Error was as great as 26 % of the true value for one Vertex instrument in laser mode (Vertex L1) but on average, Vertex hypsometers generally over estimated height by 2 - 6 % or underestimated height by 2 - 4 %. There was no significant difference between laser and sonic methods of measurement, nor were there any significant differences between instrument operators.

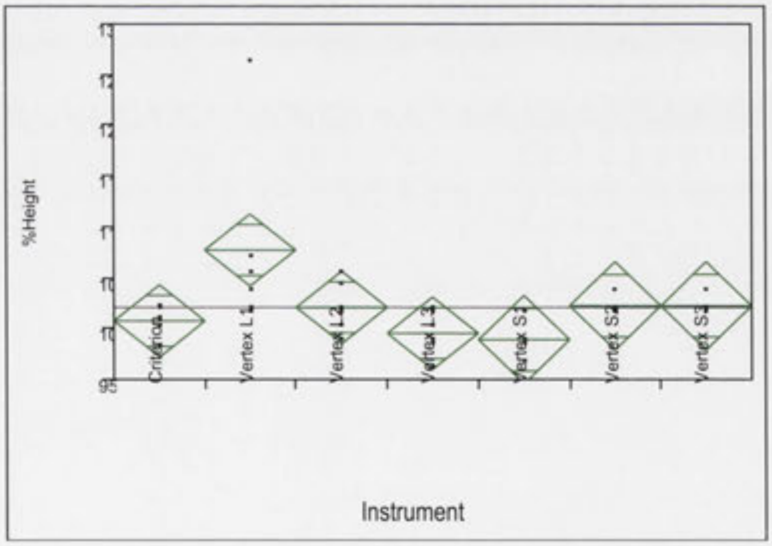


Figure A 1-1 Differences in measurement accuracy between hypsometers. Heights are given as a percentage of 'true' height (100 %) for a vertical building as measured by height stick.

Table A 1-1 One-way analysis of variance table for the test of differences between hypsometers.

One-way Anova

Summary of Fit

Rsquare	0.349344
Adj Rsquare	0.214725
Root Mean Square Error	4.236404
Mean of Response	102.0539
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	SS	Mean Square	F Ratio	Prob > F
Instrument	6	279.44361	46.5739	2.5951	0.0389*
Error	29	520.46645	17.9471		
C. Total	35	799.91005			

Means for Oneway Anova

Level	Number	Mean	Std Error	Lower 95 %	Upper 95 %
Criterion	6	100.757	1.7295	97.22	104.29
Vertex L1	6	107.703	1.7295	104.17	111.24
Vertex L2	6	102.083	1.7295	98.55	105.62
Vertex L3	6	99.538	1.7295	96.00	103.07
Vertex S1	4	98.905	2.1182	94.57	103.24
Vertex S2	4	102.229	2.1182	97.90	106.56
Vertex S3	4	102.229	2.1182	97.90	106.56

Std Error uses a pooled estimate of error variance

Appendix 2 : Soil chemical methods

A 2-1 N and P Digestion Procedure for Soils - Forestry Method

(adapted from Rayment and Lyons (2011))

Materials:

1. Sulphuric acid 98 %.
2. Hydrogen Peroxide 30 %.
3. Heavy walled Pyrex digestion tubes.
4. Digestion Block.
5. Soil samples air dried and passed through a 2mm sieve.

Reagent Preparation:

Digestion Acid

1. Dissolve 600g K_2SO_4 in 2 L of Concentrated sulphuric acid H_2SO_4 by heating in a 5 L conical flask until solution is clear. Use a magnetic stirrer.
2. When cool transfer to a storage bottle fitted with a dispenser.

Copper Catalyst

Dissolve 13.22g of $CuSO_4.5H_2O$ or 18g of $CuSO_4.10H_2O$ in 100 ml of distilled water.

Digestion Procedure:

1. Weigh 0.2 - 0.25 g of soil into each digestion tube. Record the weight of soil added.
2. Add 1.33 ml of copper catalyst and leave over night.
3. In the morning add 5 ml of digestion acid to each tube and 1 ml of hydrogen peroxide.
4. Insert the tubes into the digestion block which is set at 50°C.

5. Gradually increase the temperature. When the block gets to 200°C let the tubes cool for 5-10 minutes before slowly adding 1 ml of hydrogen peroxide to each tube. Set the temperature to 350°C and continue heating.
6. When the temperature of the block gets to 350°C remove the tubes from the block and allow to cool for 15 - 20 minutes. Add another 1 ml of hydrogen peroxide. Return the tubes to the block and continue the digestion process.
7. Allow the tubes to digest until the liquid is green.
8. Dilute samples to 75 ml (line around the neck of the tube).
9. Stopper tubes and leave to settle overnight.
10. Decant solution into centrifuge tubes.
11. The samples are ready for N & P analysis using the autoanalyzer.

A 2-2 Nitrate – Cadmium reduction method (adapted from Hach Company (1996-2000))

Apparatus:

- Falcon tubes
- DI water
- Scintillation vials
- Nitrate standards
- Nitrate reagent: NitraVer5 Nitrate Reagent Powder Pillow

Procedure:

Preparation of soil extracts:

1) Extract 2.5g soil with 25 ml DI water in falcon tubes. Allow for 1 hour extraction in rotary shaker
2) Centrifuge
3) Freeze extracts until ready for analysis

Analysis using AAS:

1) Fill a scintillation vial with 25 ml of sample
2) Add contents of one Nitrate reagent powder pillow to the sample and stopper
3) Shake the vial vigorously for one minute (set a timer)
4) Wait 5 min for colour development
5) Transfer into cuvette
6) Set spectrophotometer to read at 500 nm

A 2-3 Determination of available Phosphorus (labile P) by Resin Extraction (adapted from Robertson, Coleman et al. (1999))

Apparatus:

End over end shaker

Resin strips (anion exchange membranes) 2 x 6cm

Stirrer hotplate

Spectrophotometer

Reagents:

1. 0.5M solution of hydrochloric acid (HCl). Add 50 ml of concentrated HCl to 1000 ml of deionised water (DI) water.

2. 0.5M sodium bicarbonate ($NaHCO_3$). Add 42g of $NaHCO_3$ to 1000 ml of DI water.

3. Concentrated sulphuric acid (H_2SO_4)

4. Ammonium para-molybdate

5. Polyvinyl alcohol

6. Malachite green

7. Phosphorus stock solution 50ug P/ml. Weigh 0.2195g of oven dried KH_2PO_4 (130 °C for 2 hours). Dissolve in 1000ml of DI water. Add a few drops of chloroform and store in a refrigerator.

Prepare the Secondary P standard. Pipette 100 ml of primary standard into a 500ml volumetric flask and make to volume with DI water (this gives 10ugP/ml).

Procedure:

1. Prepare reagent A.

Add 106 ml of concentrated H_2SO_4 to 500 ml of DI (never in reverse) in a 1000ml volumetric flask. Dissolve 17.55g of ammonium para-molybdate in acid and bring to volume with DI water.

2. Prepare reagent B.

Heat approximately 800 ml of DI water to 80°C and add (slowly) 3.5g of polyvinyl alcohol and stir until dissolved. Add 0.35g of malachite green and stir until dissolved. Cool to room temperature and make to volume with DI water.

*3. Convert resin strips to bicarbonate form by shaking for 10 minutes in three successive washes of 0.5M $NaHCO_3$ solution, rinsing with DI water between each equilibration.

4. Place 1g of soil and 30ml of DI water into a falcon tube. Add two resin strips (rinsed with DI water and shaken dry). Cap tube and shake for 18 hours.

5. Remove membranes from the soil/water solution and rinse with DI water and shake dry.

6. Place membranes into clean falcon tubes containing 20ml of 0.5M HCl (record weight of HCl). Shake for 1 hour.

7. Remove resin strips and rinse with DI water and store in a weak solution of HCl (0.1M).

8. The HCl solutions are ready for analysis. Dilute extracts as necessary. Most extracts will require a 1 in 5 dilution. These can be made up in small plastic vials

(capacity 6 ml). Take 800ul of extract and add 3.2ml of 0.5M HCl. This gives a 1 in 5 dilution.

9. Prepare a set of standards from the secondary phosphorus standard as follows. Make to volume with 0.5M HCl.

ml added	0	0.2	0.5	1.0	2.0	3.0	4.0	6.0	8.0	10.0
[ ] std mgP/l	0	0.02	0.05	0.1	0.2	0.3	0.4	0.6	0.8	1.0

10. To the 1 in 5 extracts add 800ul of reagent A.

11. After 10 minutes add 800ul of reagent B. Mix.

12. After 30 minutes transfer the contents of the vials to plastic cuvettes and read absorbance at 630nm using DI water as a reference.

13. Treat the set of standards in the same fashion as the samples. Take 4 ml of each standard and add 800ul of reagent A, followed by 800ul of reagent B.

A 2-4 Determination of Electrical Conductivity (EC) in soils

Materials

50 ml falcon tubes

End-over-end shaker

Deionised water

Conductivity standard

Conductivity meter

Procedure:

1. Prepare a 1:5 soil/water suspension. For example, weigh 8 g of air-dry soil (< 2mm) into a falcon tube and add 40 ml of deionised water.

2. Mechanically shake end-over-end for 1 hour.

3. Allow 20-30 minutes for soil to settle.

4. Calibrate the conductivity electrode according to the manufacturer's instructions using the conductivity standard.

5. Thoroughly wash electrodes between the measurement of conductivity standards and between soil solutions.

6. Dip the conductivity electrode into the soil solution without disturbing the settled soil

7. Record the EC value obtained when the meter is steady.

8. Rinse the electrode with distilled water and remove excess water.

9. Complete EC measurements within 4 hours of obtaining the aqueous supernatant.

9. Report EC (dSm^{-1}) on air-dry basis.

A modified version of this method was followed for the measurement of pH.

Appendix 3 : The association between *b* and *k* at the QLD case study site

There was a weak association between values of shape and taper in the QLD case study site that might offer an explanation for the curvilinear effect observed in the model. Generally, lower values of shape and taper were associated together, and higher values of shape and taper were associated together (Figure A 3-1). In some cases, higher and lower shapes and tapers were associated together, but the majority of the data fell within the first and third quadrants of the plot, indicating a stronger general association between higher values of shape and taper and lower values of shape and taper.

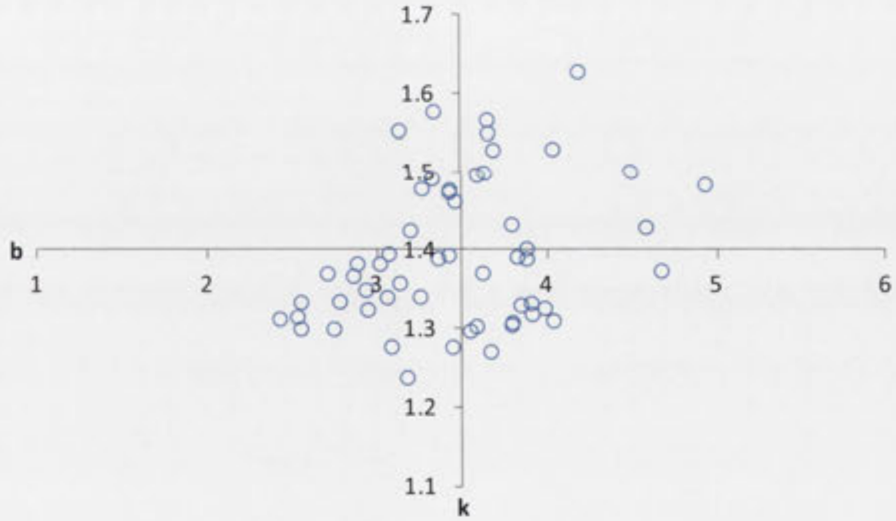


Figure A 3-1 Scatterplot of taper (k) against shape (b) with axes crossing at the overall mean values of k and b ($R^2 = 0.1$, $p < 0.05$).

Appendix 4 : Semivariograms

The spherical model is one of the most common models for fitting semivariograms and is the default model in Geostatistical Analyst. The spherical model shows a progressive decrease of spatial dependence until a particular distance, after which spatial dependence reaches a plateau. The graphs below (Figure A4.1 - 4.4) show the semivariograms fitted with spherical models that were used as the interpolator in kriging for all maps produced in Chapter 7.

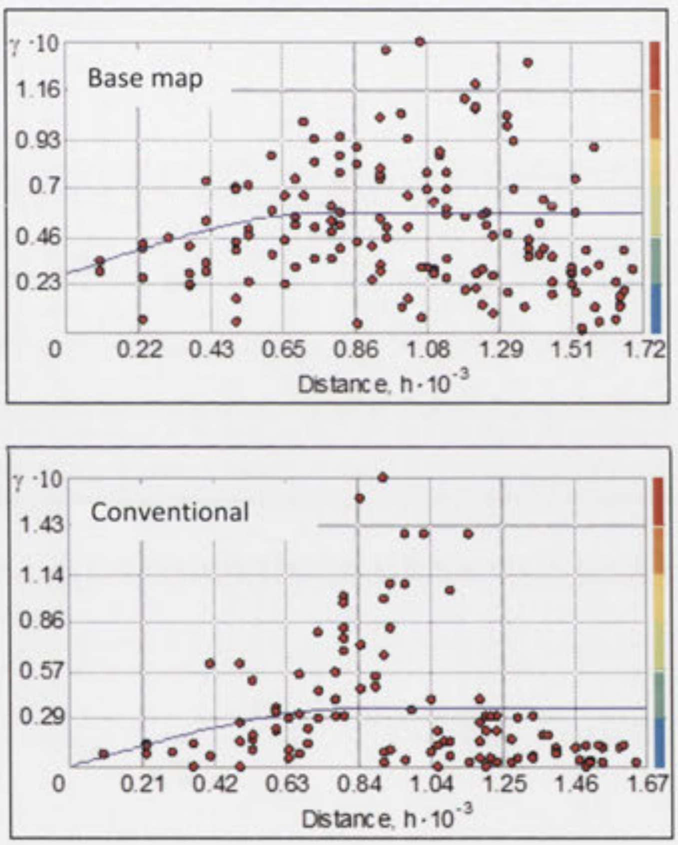
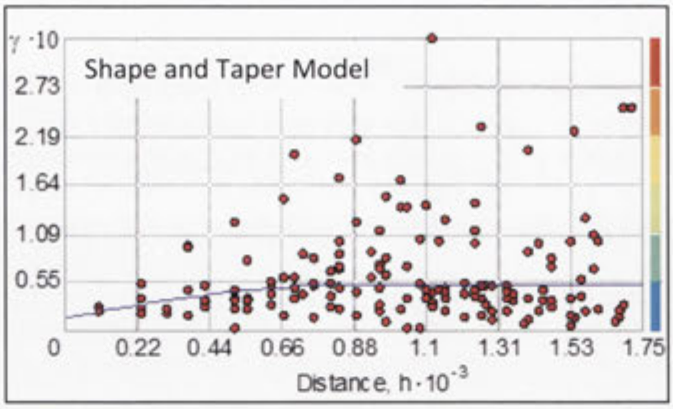


Figure A 4-1 Semivariograms for maps based on soil observations.



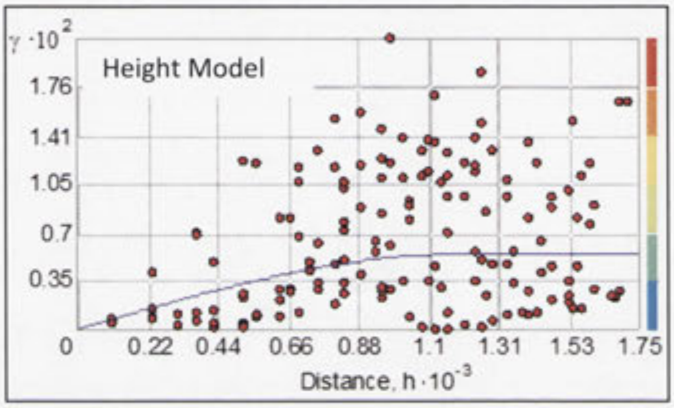


Figure A 4-2 Semivariograms for maps based on model predictions.

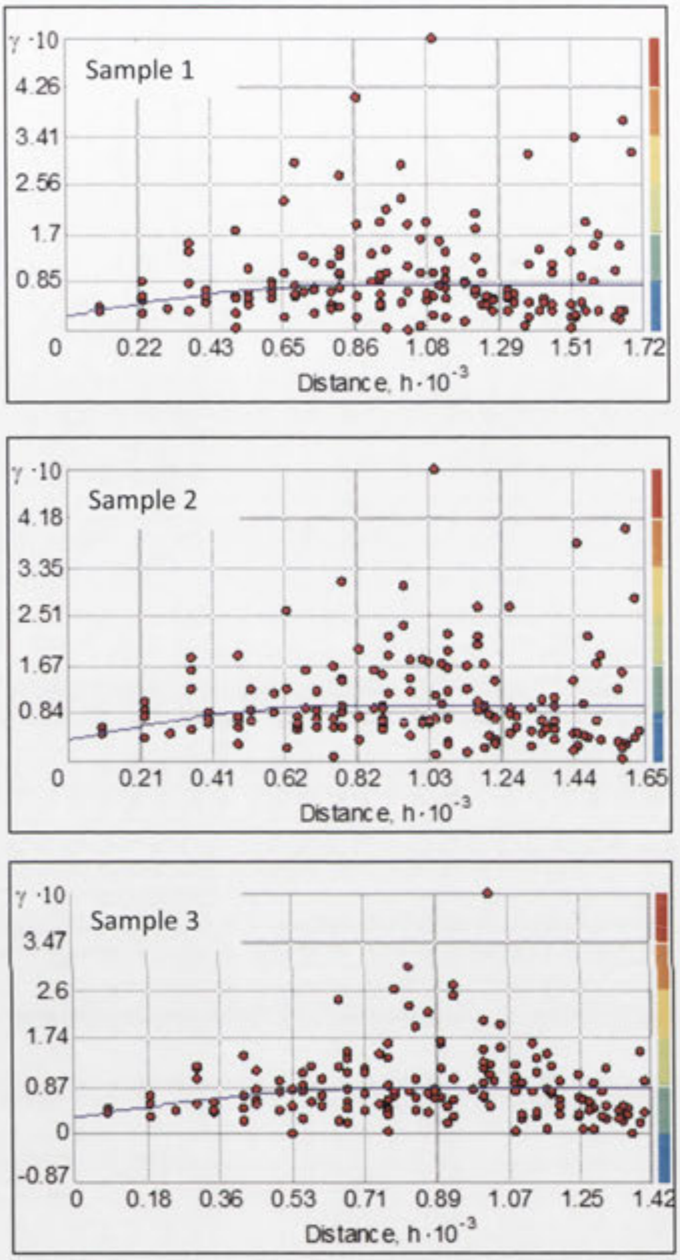


Figure A 4-3 Semivariograms for sensitivity analysis of the stem shape and taper model.

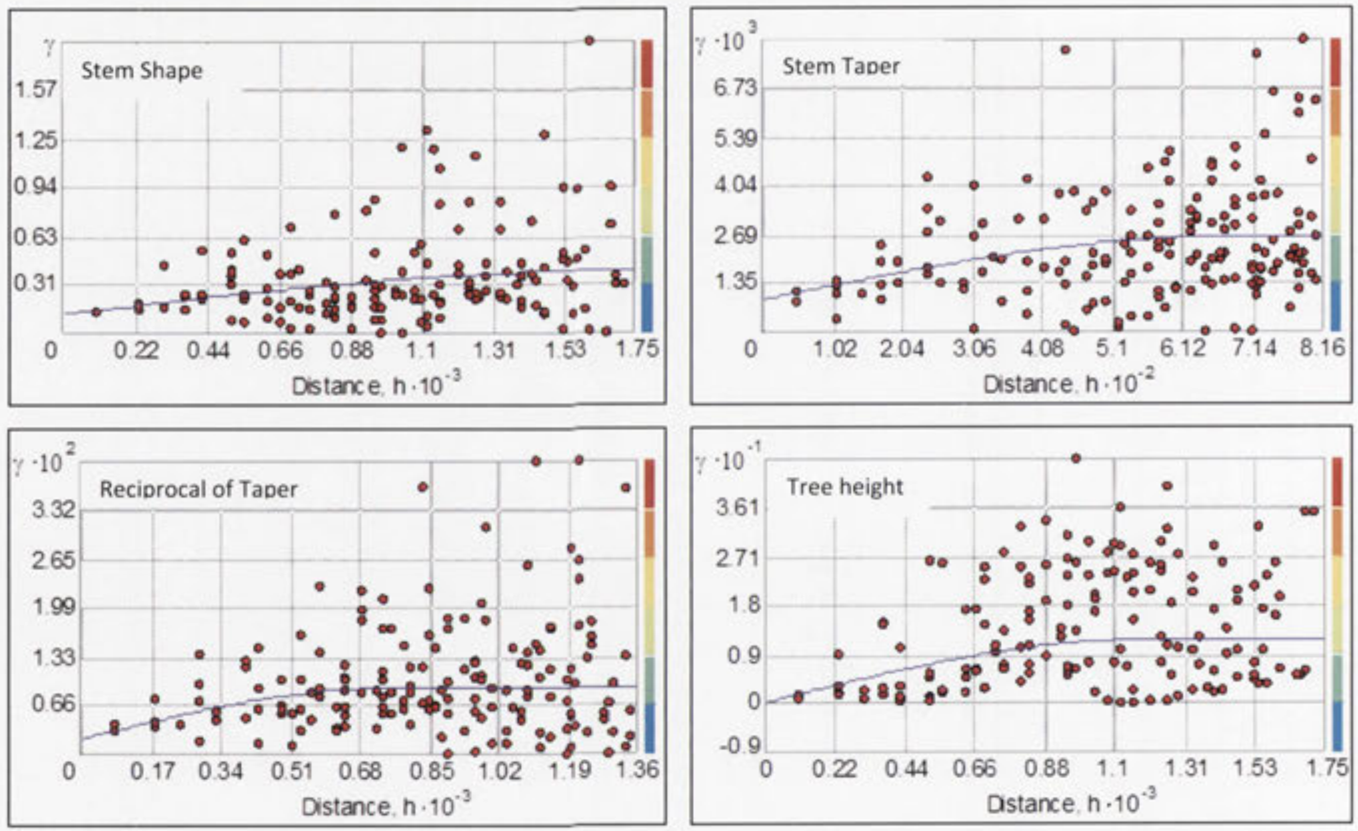


Figure A 4-4 Semivariograms for maps of individual tree parameters.

Appendix 5 : Height error sensitivity test

Table A 5-1 The effect of a ± 2 m error in individual tree height on predictions of depth class for shape (*b*) and taper (*k*) and tree height models. *'D' and 'S' denote deep and shallow soils respectively.*

Tree	Error in Height (m)	Observed Depth Class	Value			% error			Predicted Depth Class	
			b	*k*	Height (m)	*b*	*k*	Height (m)	*b/k*	Height (m)
	-2.0		6.67	1.59	22.2	8.64	0.04	8.26	S	S
F2.6	**0.0**	**Deep**	**7.3**	**1.59**	**24.2**	**0.0**	**0.0**	**0.0**	**S**	**S**
	2.0		7.93	1.59	26.2	8.64	0.03	8.26	D	D
	-2.0		6.4	1.62	19.6	9.7	0.03	9.26	D	S
F1.5	**0.0**	**Shallow**	**7.08**	**1.62**	**21.6**	**0.0**	**0.0**	**0.0**	**S**	**S**
	2.0		7.77	1.61	23.6	9.7	0.04	9.26	S	S
	-2.0		2.51	1.41	11.3	16.22	0.09	15.04	S	S
P3.0	**0.0**	**Deep**	**2.99**	**1.41**	**13.3**	**0.0**	**0.0**	**0.0**	**S**	**S**
	2.0		3.48	1.41	15.3	16.21	0.06	15.04	D/S	D
	-2.0		2.25	1.43	9.4	19.28	0.14	17.54	S	S
P1.3	**0.0**	**Shallow**	**2.79**	**1.43**	**11.4**	**0.0**	**0.0**	**0.0**	**S**	**S**
	2.0		3.33	1.43	13.4	19.25	0.1	17.54	S	D/S
	-2.0		6.64	1.39	27.2	7.08	0.02	6.85	D	D
F2.0	**0.0**	**Deep**	**7.15**	**1.39**	**29.2**	**0.0**	**0.0**	**0.0**	**D**	**D**
	2.0		7.65	1.39	31.2	7.08	0.02	6.85	D	D
	-2.0		2.64	1.35	11.3	16.24	0.07	15.04	D	S
P3.3	**0.0**	**Shallow**	**3.15**	**1.35**	**13.3**	**0.0**	**0.0**	**0.0**	**D**	**D/S**
	2.0		3.66	1.35	15.3	16.22	0.05	15.04	D	D
	-2.0		2.61	1.33	13.1	14.38	0.11	13.25	D	S
KG3	**0.0**	**Deep**	**3.05**	**1.33**	**15.1**	**0.0**	**0.0**	**0.0**	**D**	**D**
	2.0		3.49	1.33	17.1	14.38	0.08	13.25	D	D
	-2.0		1.97	1.27	11.6	15.72	0.06	14.71	D	S
KR.0	**0.0**	**Shallow**	**2.33**	**1.27**	**13.6**	**0.0**	**0.0**	**0.0**	**D**	**D**
	2.0		2.7	1.27	15.6	15.72	0.05	14.71	D	D
	-2.0		2.38	1.47	9.6	18.79	0.13	17.24	S	S
P2.3	**0.0**	**Shallow**	**2.93**	**1.47**	**11.6**	**0.0**	**0.0**	**0.0**	**S**	**S**
	2.0		3.49	1.47	13.6	18.78	0.09	17.24	S	D/S
	-2.0		2.49	1.33	12	15.45	0.09	14.29	D	S
P3.2	**0.0**	**Shallow**	**2.94**	**1.33**	**14**	**0.0**	**0.0**	**0.0**	**D**	**D**
	2.0		3.39	1.33	16	15.44	0.07	14.29	D	D
	-2.0		9.26	1.81	21.3	8.96	0.06	8.58	S	S
F1.0	**0.0**	**Shallow**	**10.17**	**1.81**	**23.3**	**0.0**	**0.0**	**0.0**	**D/S**	**S**
	2.0		11.08	1.81	25.3	8.96	0.05	8.58	D	D
	-2.0		6.61	1.39	25.3	7.6	0.02	7.33	D	D/S
F2.4	**0.0**	**Deep**	**7.15**	**1.39**	**27.3**	**0.0**	**0.0**	**0.0**	**D**	**D**
	2.0		7.7	1.39	29.3	7.6	0.02	7.33	D	D